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EVALUATION OF RADIOACTIVE FALL-OUT

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Armed Forces Special Weapons Project
Washington, D.C.

From: CIC

September 15, 1955

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NOTICE

This is an extract of AFSWP-978, Evaluation of Radioactive Fall-Out, which remains classified SECRET/RESTRICTED DATA as of this date.

Extract version prepared for:

Director
DEFENSE NUCLEAR AGENCY
Washington, D.C. 20305

15 May 1981

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FOREWORD

This report has had classified material removed in order to make the information available on an unclassified, open publication basis, to any interested parties. This effort to declassify this report has been accomplished specifically to support the Department of Defense Nuclear Test Personnel Review (NTPR) Program. The objective is to facilitate studies of the low levels of radiation received by some individuals during the atmospheric nuclear test program by making as much information as possible available to all interested parties.

The material which has been deleted is all currently classified as Restricted Data or Formerly Restricted Data under the provision of the Atomic Energy Act of 1954, (as amended) or is National Security Information.

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Radioactive Fall-Out
Biological Hazards
Radioactive Debris
Physical Phenomena

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this report is to assess the magnitude and extent of the hazard to human life imposed by radioactive debris deposited in the human environment by large numbers of nuclear weapons. Known physical facts, data from nuclear weapon test experience, and pertinent theoretical considerations are utilized to evaluate the extent of the hazard.

LETTER OF PROMULGATION

This report, Evaluation of Radioactive Fall-out, is published in order to present the facts to the extent that they are known, about the radiological situation following the detonation of nuclear weapons; and the facts and opinions relating to the biological hazards likely to be encountered from radioactive fall-out.

The discussion given in the report, the evaluation presented and the conclusions drawn are those for both the close-in fall-out and the world-wide contamination problems and the interrelationship of the two. General concepts are developed from available data. Detailed treatment of several aspects of the fall-out problem may be found in the references listed in the report.

It is planned to keep the problem under continuous active study and it is expected that, as more information becomes available, supplementary reports will be presented.

G.R. Luedecke
A. R. LUEDECKE
Major General, USAF
Chief, AFSWP

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AFSWP TECHNICAL REPORT

AFSWP-978

EVALUATION OF RADIOACTIVE FALL-OUT

by

Roy D. Maxwell
Roger W. Paine, Jr.
Thomas E. Shea, Jr.
Harold H. Mitchell
Edwin R. Ballinger

WEAPONS EFFECTS DIVISION

Armed Forces Special Weapons Project Reports are documents prepared by staff sections of this headquarters for the purpose of disseminating latest available information to authorized agencies of the three services. They are official AFSWP documents and as such represent the AFSWP position on information contained.

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September 1955

HEADQUARTERS, ARMED FORCES SPECIAL WEAPONS PROJECT
Washington 25, D. C.

ABSTRACT

The purpose of this report is to assess the magnitude and extent of the hazard to human life imposed by radioactive debris deposited in the human environment by large numbers of nuclear weapons. Known physical facts, data from nuclear weapon test experience, and pertinent theoretical considerations are utilized to evaluate the extent of the hazard. A discussion of the physical phenomena is presented to show the mechanisms whereby radioactive particles may be formed. Consideration was given to the changes in the intensity of a fall-out field of radioactive debris as variations are made in the proximity of the detonation to the earth's surface, the magnitude of the fission yield, the total yield of fission and fusion weapons and the meteorological conditions immediately before and shortly after an atomic detonation. The degree of local hazard involved will in every case at least equal or exceed that of the world-wide hazard when expressed as a function of unit areas.

The biological significance of the effects of ionizing radiations of various levels on humans, the beneficial effects of shielding against high levels of radiation during the early decay of the radioactive fall-out field, the genetic effects, and the significance of internally deposited radioactive isotopes as carcinogens are discussed in the light of the presently existing data together with projected calculations of possible effects. For long-term carcinogenic effects, strontium-90 is considered to be the most hazardous of the radioisotopes spread both locally and world-wide. It appears likely that the number of nuclear weapon detonations required to cause a world-wide long-term strontium-90 hazard would be so large as to result in devastation of much of the habitable world area from the immediate destructive effects of the weapons.

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I. INTRODUCTION

The purpose of this report is to assess the magnitude and extent of the hazard to human life imposed by radioactive debris deposited in the human environment by large numbers of nuclear weapons. The large amount of data which has been accumulated from field tests of nuclear weapons, laboratory findings, and field research is so voluminous that an evaluation of these is indicated. The evaluation is made in the light of known facts of nature, nuclear weapon test experience, and pertinent theoretical considerations.

All explosive nuclear devices known to have been constructed or envisioned thus far utilize either wholly or in part a nuclear process known as fission to achieve the energy release desired. The energy yield of a pure fission device is limited by the fact that the quantity of fissionable material that can be assembled in a given configuration cannot safely exceed a particular amount, called a critical mass. This amount can be increased indefinitely by expanding or dispersing the configuration; however, a practical limit is soon reached because the size of the configuration becomes cumbersome and the problem of assembly at the desired instant of detonation becomes more and more difficult.

A companion process to the fission process is that of fusion. Although the unit energy yield is less, there is no criticality problem for fusionable materials; thus large quantities of fusionable material can be engineered into weapon designs with no attendant nuclear safety problem. "Boosted" fission weapons and all thermonuclear devices make some use of this process. Since very high temperatures are required to initiate the fusion reaction, a fission "trigger" or primary is a necessary component of the fusion devices successfully built thus far.

The fission process is a phenomenon whereby radioactive nuclides are formed from the splitting of large atoms, with concurrent release of large amounts of energy. Under the proper physical conditions,

these nuclides may become associated with particulate matter from other bomb debris, from dust in the atmosphere or material raised by the explosion, or from moisture condensed in the atmosphere to form rain, and thus will be brought to the earth's surface and become a potential radiological hazard. On the other hand, the nuclides formed in the fusion process (except for the unburned tritium) are not radioactive and do not, of themselves, increase the potential radiological hazard.

The radioactive fragments formed in the fission process are chemical elements ranging from zinc to europium, the lowest and highest atomic weight elements formed, respectively. A relatively small quantity of radioactive atoms which are not fission fragments are found following atomic detonations. This activity results from the action of neutrons on the nuclei of certain stable atoms.

U.S. nuclear weapon war and test experience consists of 65 shots to date. Detonations have been carried out at high, intermediate, and low altitudes, on towers and on and under both land and water surfaces, over a range of yields from less than a kiloton to about 15 megatons TNT equivalent. In addition, the United Kingdom and Soviet Russia have conducted nuclear weapon tests, and much data from the tests by the United Kingdom are available to us.

Ground surface and underground bursts result in the incorporation of radioactive fission fragments and the small amount of induced radioactive materials which are formed, on or into earth particles which provide a vehicle for bringing the contaminant promptly from the atomic cloud to the surface of the earth. An air burst, on the other hand, provides no ready means for bringing the contaminant down quickly, with the result that there is very little local fall-out from this type of burst.

The height to which an atomic cloud rises above the burst point depends primarily upon the yield of the detonation. After cloud stabilization, the speed and direction of the winds at all altitudes through which the particles must fall determine the direction of expected

fall-out, and the yield and type of bomb together with the proximity of the detonation to the earth determine the total amount and kind of debris available for fall-out. After local fall-out is completed, the process continues in more remote areas to a lesser and lesser degree over a period of months or even years as the cloud is taken by the wind currents around the world.

Particles from close-in fall-out and world-wide diffusion have been collected by several different sampling methods at altitudes ranging up to 90,000 feet. Radiochemical analysis of these particles shows the presence of many artificially radioactive isotopes. The percentage composition of these, allowing for radioactive decay, generally parallels the yield of the element from the fission process, although certain elements have been found to vary from the expected quantity for physically explainable reasons.

There are certain radioactive elements which are known to be biologically hazardous when deposited in humans and animals. Examples of these are strontium-89, strontium-90, and iodine-131, all of which are formed in considerable quantities as a consequence of fission. These potentially hazardous fission products may be taken into the body by either inhalation or ingestion, and tend to collect in certain parts of the body such as the bone or thyroid, where their damage is done over extended periods of time.

Very little definitive information exists on human response to ionizing radiations, and one must rely largely on animal data, supplemented by data from a limited number of accidental human exposures, in evaluating the fall-out hazard.

In the CASTLE test series in the spring of 1954, 239 Marshallese natives and 28 American servicemen were accidentally exposed to sublethal amounts of fall-out radiation. Clinical studies of these human subjects proved that quantities of radiation biologically damaging to humans may be received from this type of radioactivity at great distances from the point of origin. The biological damage, although kept sublethal because of prompt evacuation, included beta burns when radioactive particles were in direct contact with the skin, and hematological

changes from the gamma radiation of the particles not in direct contact with the individual. There were indications of small but measurable quantities of internally deposited radioactive isotopes.

Animal experimentation has shown that external irradiation to the gonads can cause gene mutations. Most of these mutations are deleterious and may cause eventual genetic death. In order to assess the significance of this phenomenon the basic genetic data have been extrapolated to man as realistically as possible in the light of current knowledge. The basic biological extrapolation has been interpreted in terms of the known or predicted physical radiological exposure data.

All damaging radiations from fall-out are attenuated in some degree by matter interposed between the source and the receiver. Small amounts of material, such as a layer of heavy clothing, will absorb almost completely the alpha and beta radiations from fall-out. The gamma radiation from fall-out cannot be completely stopped by shields, but even minimal shielding can be quite effective in reducing gamma radiation received to tolerable levels.

Thus it can be seen that the phenomonology of nuclear weapons is such that the physical effects determine the biological parameters to be evaluated. The hazard created in the close-in fall-out area by a large surface detonation is greater by several orders of magnitude than was ever observed until the high levels of fall-out radiation were discovered following the Bravo shot of the CASTLE series. The biomedical data presented indicate that absolute safety and freedom from injury are unattainable since some radiation effects such as genetic damage and possibly carcinogenesis do not have a threshold of injury as far as can be determined. It must be borne in mind that the population at risk is larger by far than was ever considered in programming for adequate public health practices or disaster handling for the country at large. A good educational program regarding the hazards involved, leading to utilization of the beneficial effects of all available shielding, early evacuation and adequate decontamination procedures will avoid many unnecessary casualties should such a catastrophy as a nuclear war ever occur.

II. PHYSICAL ASPECTS OF THE FALL-OUT PROBLEM

A. Radioactive Materials Formed In A Nuclear Detonation.

The quantity of radioactive material created as fission products in the detonation of a fission weapon is known to depend upon the total energy release of the weapon. Some methods of calculation of total fission yields utilize the number of fissions per kiloton, which gives approximately 1.38×10^{23} fissions occurring per KT of fission yield[1/], resulting in 2.76×10^{23} radioactive fission fragments per KT. This value includes all of the immediate fission products, some of which decay with very short half-lives, while others may give rise to decay chains consisting of several isotopes, some of which may have longer half-lives, resulting in their decay over a period of months or years. All emit one or more beta particles and most emit one or more gamma rays. There are approximately 170 isotopes ultimately formed from a total of 35 elements known to result from the fission process. Some of these isotopes are formed directly from fission; others form in part from direct fission and partly from decay chains. If the same isotope is formed by the two processes, the total isotope concentration is the sum of the two. Two examples of decay chains which form the same elements but different isotopes as indicated by their different half-lives are:

$$\text{Germanium-77} \xrightarrow[\text{12 hours}]{\beta^-} \text{Arsenic-77} \xrightarrow[\text{40 hours}]{\beta^-} \text{Selenium-77 (Stable)}$$

$$\text{Germanium-78} \xrightarrow[\text{2.1 hours}]{\beta^-} \text{Arsenic-78} \xrightarrow[\text{1.5 hours}]{\beta^-} \text{Selenium-78 (Stable)}$$

It is convenient to discuss the quantity of radioactive materials formed in a nuclear detonation in terms of the value at one hour after detonation, expressed in curies per KT. At this H+1 hour reference time, there are approximately 3.0×10^{8} curies of gamma-active fission

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1/ Spence, R. W., Bowman, M.C., Radiochemical Efficiency Results of SANDSTONE Tests. Scientific Director's Report of Atomic Weapons Test Annex 1. SECRET Restricted Data.

products formed per KT of fission yield, plus 1.1 x 10^8 curies of beta-active products, for a total of 4.1 x 10^8 curies of fission product activity. The average effective gamma ray energy in a fission product field is about 0.7 Mev, so that if 1 million curies of mixed fission products are spread uniformly over a one square mile plane surface, the gamma radiation intensity measured 3 feet above that surface would be about 4 r/hr.

The specific yields of radioactive materials have been studied in a variety of ways. The Hunter-Ballou studies[2/*] on slow neutron fission, and Coryell-Sugarman compilation[3/] can be used to obtain percentage values. Zinc-72 is the atom of lowest mass and gadolynium-160 the greatest of those found to result from fission. Figure 1 indicates the variation of fission yield with mass number, with fission yield expressed as a per cent, for U^{235}, U^{238}, and Pu^{239}. The total adds up to 200% since each fission gives two fission products. Fast fission of uranium-238, plutonium-239, and uranium-235 results in approximately the same fission yield values with the largest difference in the middle zone where the value varies from 0.01% for uranium-235 to 0.05% for uranium-238. Thus, the various mixtures of fissionable material and uranium-238 tamper material which may be present in a weapon have relatively little effect percentage-wise on the relative amounts of radioactive isotopes formed. The first peak in Figure 1 includes strontium-89 and strontium-90 and the second peak contains iodine-131, which are

* Hunter-Ballou studies are an accurate measurement of the percentage of radioisotopes obtained from a laboratory bombardment of uranium and plutonium by slow neutrons. The results of the observations in the laboratory are compared with the percentages of radioisotopes found in fall-out particles and variations between the laboratory and test percentages are an indication of fractionation. This approach is considered the only accurate method possible to calculate percentage yield. The Coryell-Sugarman studies provide similar information about the percentages of isotopes produced in the laboratory from the bombardment of fissionable materials with fast neutrons.

2/ Hunter, H.F., Ballou, N.E., Simultaneous Slow Neutron Fission of U-235 Atoms, I. Individual and Total Rates of Decay of the Fission Products, USNRDL ADC-65, 1949.

3/ Coryell, C.D., Sugarman, N., Radiochemical Studies, The Fission Products, The National Nuclear Energy Series, Book 2: Part V, 1951.

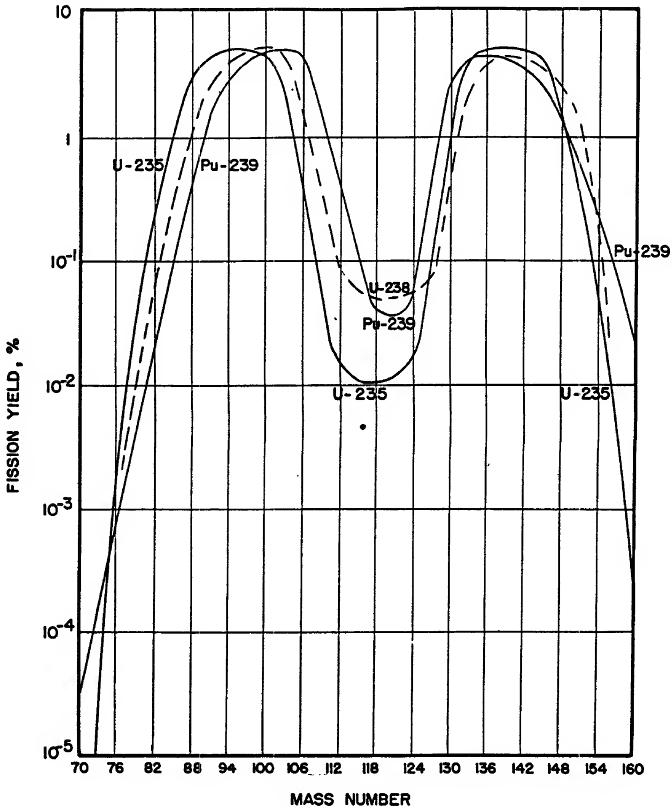

Fig. 1. Comparison of the Yield-Mass Curves for the Fission of U-235, U-238, and Pu-239, Fission Yields for the Fission of Pu-239 with Fast Neutrons.

three isotopes of biological importance. The tests of megaton yield weapons during the CASTLE series revealed that

These relative fission and fusion values will change with weapon design, so that in the future more of the total energy may be derived from the fusion process, resulting in less radioactive bomb debris. As an approximation valid for current U.S. thermonuclear weapons, it is estimated that 3.0×10^{12} curies of gamma radioactive material will be available from a thermonuclear weapon at one hour after burst time for some mechanism of deposition, either as early or as late fall-out.

In the case of thermonuclear weapons the general shape of the contour pattern involved in fall-out will depend upon the total energy yield, but levels of radiation will depend upon the mixed fission product yield.

The radioactive decay of mixed fission products has been found to follow the form $I = I_1 t^{-1.2}$, in which I = radiation reading at time t in roentgens per hour; I_1 = reading at one hour in roentgens per hour; t = time in hours after initial reading. All radioactive isotopes decay at a specific rate determined by the half-life of the isotope, and the total fission product decay law is the weighted mean of all half-lives found in the mixture. Thus, of the total number of isotopes formed, half-lives are found to vary from a fraction of a second to several years. The $I = I_1 t^{-1.2}$, or $t^{-1.2}$ decay rate as it is frequently stated, holds rather well for times up to 120 days; then, gradually, the half-life decay of specific long-lived isotopes begins to predominate, particularly after one year.

Because of the change with time in specific isotope concentration, a change in the over-all energy spectrum of the mixture would be expected. This in fact does occur, and the gamma radiation is found to

soften with time. The change is rather small. Initially, the mean effective gamma energy is a little over 1 Mev. After 10 days the energy of the major portion of the isotopes present shows two peaks, one at about 0.5 to 0.7 mev and the other (and smaller) at about 1.3 mev, with very little change at later times.

It is sometimes useful to speak of quantities of specific isotopes formed and distributed because of differences in physical, chemical or biological properties which might be of interest for a particular problem. The average weight of any isotope formed can be found by utilizing the percentage yield curve. The yield in curies per gram can be estimated to an approximation by the formula $\frac{1}{7.66 \times 10^{-9}\ AT_{1/2}}$, where A = atomic weight; $T_{1/2}$ = radioactive half-life of the isotope in days. Thus, to use the three biologically important isotopes previously cited as examples, there will be 1.24×10^5 curies of iodine-131, 2.62×10^4 curies of strontium-89, and 2×10^2 curies of strontium-90 formed per KT of fission yield. From the number of curies of activity calculated for the three examples used, it can be seen that the half-life of an isotope is a very important factor in the calculation. As a consequence, the bulk of the gamma radiation emitted early in the fall-out field is due to the large number of curies of energetic gamma emitters from a relatively small percentage yield of short half-lived isotopes.

The fusion process does not contribute to the quantity of radioactive materials which are available for fall-out except those formed from induced activity, which will be discussed later. It does make a measurable contribution, however, to the low level of tritium which is normally found in the atmosphere resulting from cosmic radiation. This quantity of tritium is approximately [ ] Kg per MT of fusion energy release (1.24×10^8 curies per MT). The possibility of dangerous concentrations of tritium in the atmosphere is very remote because of the great dispersion effect of the winds, the tendency toward upward diffusion of light gases, and the slow reaction rate of tritium with oxygen to form water.

Neutron-induced activity in the soil has been a subject of considerable study. In sandy soil, radiosilicon may be formed with a 170-minute half-life, emitting a 1.8 mev beta but no gamma, decaying to stable phosphorous. In clay soil, radioaluminum may be formed with a 2.4 minute half-life, emitting 2.7 to 3.3 mev betas and a 1.8 mev gamma, and decaying to stable silicon. In the coral sand of the Pacific Proving Ground a considerable quantity of calcium-45 may be formed. Its relatively long half-life of 180 days, a 0.26 mev beta with no gamma, and its position of importance in the biological system, make it interesting. However, the quantity formed by detonation of a weapon over average soil would not result in a sufficient amount of calcium-45 to constitute a hazard. Radiosodium may be formed in areas where the concentration of sodium is high, and this may become important in detonations over and in sea water. It is the considered opinion of most investigators that for surface or near-surface bursts, induced radioactivity in elements of the soil and water is of minor importance to the over-all fall-out hazard, particularly so after the first day following the detonation. The area where ground induced activity may be important is limited to the area around ground zero. The amount of activity formed depends upon the type of bomb, height of burst, and type of soil over which the detonation occurred. Neutron-induced activity in the ground is apt to be of greatest importance when the weapon is burst in such a position that the fireball is just clear of the ground. In this case, there would be very little fission product activity deposited locally, as will be discussed later; however, the induced activity at ground zero might be as much as 2000 r/hr at one hour after burst time for certain high neutron flux weapons such as

It is important to note that the $t^{-1.2}$ radioactive decay factor discussed previously would not be applicable in this case. The early decay would be apt to be slower but the later decay would be faster than the $t^{-1.2}$ formula would indicate. For example, high sodium content in the soil would probably give an effective half-life of about

14 hours for the ground-induced activity.

One of the phenomena of nuclear weapons is the high flux of neutrons of all energies. The number of fast or high energy neutrons resulting from the detonation of larger weapons is sufficient to cause a large fission yield from uranium-238 when used as a tamper for the implosion process. In addition to the fission reaction, the capture process of neutrons of intermediate energies by the uranium-238 yields appreciable quantities of neptunium-239. This decays with a 2.3 day half-life to plutonium-239, emitting a hard beta and gamma. Thus, the quantity of plutonium-239 ultimately formed depends on the quantity of uranium-238 used in the tamper. Part of the radiation hazard found following the CASTLE series shots, particularly after Bravo, resulted from the large quantities of uranium-238 which were irradiated. The energy of the neptunium decay radiations is in the biologically hazardous range. The proportion of neptunium radiations emitted relative to the fission product emissions was sufficient to alter the $t^{-1.2}$ decay rate appreciably during the period from about H+10 hours to D+10 days, so that data studied must consider this variation.

but the quantity is still insufficient to be an independent hazard in a close-in fall-out field.

B. Radioactive Particle Formation.

When a nuclear weapon is detonated, all fission fragments, unfissioned active material, the bomb tamper, and the bomb casing are included under the name of bomb debris. The proximity of the fireball to the ground, the nature of the terrain, and the yield of the weapon used, largely determine the ultimate amount of soil which is mixed with the bomb debris to form radioactive fall-out particles. The final fate of bomb debris which is mixed with the dirt may be influenced to a considerable extent by the chemical composition of the fall-out vehicle.

Detonations at a sufficient height so that the fireball does not reach the ground result in a distribution of atoms of bomb debris with

no ready vehicle for local fall-out[4]. The fireball engulfs enough air to insure an adequate supply of oxygen to enable the atoms to form oxides when the proper temperature is reached. Although many of the elements combine to form oxides, some unite with oxygen to form negative radicals while the halogens form halides which combine with the strongly electropositive elements to form compounds. The noble gases, krypton and xenon, remain in the atomic state awaiting radioactive decay to change them to elements which can form an oxide or halide. These two noble gases are precursors for strontium and barium, respectively.

The cloud rising from the point of detonation carries all these materials as separate molecules, but with the rapid cooling of the fireball, from 7000°K to approximately 2000°K in one to five seconds, oxides with similar condensation temperatures become available to form small mixed crystals for later incorporation into fall-out particles. It is reasonable to assume that this condensation may be aided by the intense ionization that accompanies the nuclear explosion, although there is no definitive data to support this statement. The tiny crystal nuclei, containing the mixture of oxides, halides and noble gases, are carried throughout the cloud, where they can be absorbed on dust particles or grow by self-nucleation as a result of many collisions. As a result of aggregation, they attain sufficient bulk to be carried to earth by free fall or mass air transport. Eddy currents tend to diffuse and scatter the particles, in some cases hastening and in others retarding the return to the earth.

The sizes of fall-out particles from an <u>air burst</u> are not well documented. Investigators agree that the size distribution during the early life of the cloud is logarithmic, with the numbers in the aggregation decreasing as the diameter of the individual particle increases

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4/ Greenfield, S.M., et al., Transport and Early Deposition of Radioactive Debris from Atomic Explosions. Project AUREOLE of the RAND Corporation, July 1954, SECRET Restricted Data.

from the median. The examination of samples by electron microscope shows the maximum number to occur below 0.1 micron in diameter, with particle sizes as low as 0.01 micron being present. The particle size of 0.9 micron is theorized to contain most of the radioactivity from an air burst. The particle size of 0.2 to 8 microns is the range of particle size which has been found to be an inhalation hazard, inasmuch as such particles can be inhaled into the lungs and retained. The radioactivity from these particles can exert its influence on the lung where the particles lodge if insoluble, or may be transported to other tissues if the particles are in a soluble form.

Unlike an air burst with its fine particles, when an atomic weapon is detonated on or near the ground so that the fireball intercepts the surface, molten earth is drawn into the cloud and is present when the condensation phase of the oxidized atoms of the bomb debris occurs. The size, shape and distribution of the particles formed are influenced by the chemical composition and the original particle sizes of the earth which is fused. The two test sites normally used by the United States for atomic bomb testing have widely different soils; at the Nevada Test Site silicates predominate, while at the Pacific Proving Ground the land surface is almost entirely calcium carbonate.

When the earth contains SiO_2, as it does at the Nevada Test Site, molten silicate is drawn up into the cloud[5/] and swept around in typical toroidal motion. The molten silicate most significant for particle formation is that portion which is swept up with the fireball and only reaches temperatures of 2,000° to 2,800° C. It is theorized that these heated particles are swept around at the top of the stem or in the cloud in an atmosphere of fission products, plutonium and bomb case fragments. It is further hypothesized that condensation or agglomeration results in the bomb debris being deposited uniformly in the center of the molten silica. As the particles cool, they tend to pick

5/ Tompkins, R. C., Krey, P. W., Radiochemical Studies on Size-graded Fall-out and Filter Samples from Operation JANGLE. Radiological Division, U. S. Army Chemical Corps, August 1952, SECRET Restricted Data.

up less activity because many of the short-lived isotopes have decayed, and with the growth of the cloud, fewer of those isotopes remaining can be contacted by any one particle. The particles, as they cool below 1,700° C, are still able to pick up some activity on the outer surfaces. Krypton-89, krypton-90, and xenon-140, which are present during the formation of the fireball and are precursors for strontium-89, strontium-90, and barium-140, have very little tendency to be incorporated uniformly in the particles during the early stage of formation. These noble gases, when associated with a particle, are deposited unevenly on the surface layers and distributed along with relatively large deposits of inactive debris which were drawn toward the fireball too late to form fused radioactive particles. Tests made on sample particles from Nevada shots indicate that even in the case of fused particles, the radioactivity tends to concentrate toward the outside of the particle.

The shape of the Nevada particles is essentially spherical and they may differ markedly one from the other in physical appearance. Some are black and ferromagnetic; others resemble glass beads; some appear to be glass beads that have been fractured, but all appear under the microscope to be different from the inactive soil collected in the same fall-out. The particles which have been collected in the Southwest Pacific, although different in chemical composition from those collected in Nevada, follow essentially the same general pattern. The size of these particles ranges from 0.02 micron to 1,000 microns.

In the case of Pacific Proving Ground shots, calcium carbonate in the ground is heated to a very high temperature and is fused and vaporized, generally resulting in particles so fine that they are relatively unimportant as vehicles for immediate fall-out. However, a portion of the soil passes into the fireball and is heated to a temperature of about 2000° to 2700° C, which is sufficient to decompose the calcium carbonate to calcium oxide and also to soften the particle or to even melt it at the higher temperature given.[6] When such particles become

6/ Adams, C. E., The Nature of Individual Radioactive Particles; II. Fall-out Particles from M-Shot, Operation IVY, USNRDL-408, July 1953, SECRET.

mixed with the bomb debris in the cooling mushroom cloud, they absorb activity. This radioactivity is not uniformly distributed throughout the particle but is absorbed primarily on the surface. It is also possible for two or more particles to aggregate and in this way more heterogeneous systems are formed. These particles are usually above 100 microns in size, and tend to fall out locally.

The fall-out particles from the water surface (barge) shots of the CASTLE series were, for the most part, carried in water droplets. Samples were collected, but the data give very little information on the transport or deposition mechanisms.

An underground burst is one in which the center of detonation lies below the surface of the earth. Particle formation takes place as the earth particles and hot gases rise above the ground in an inverted cone or column. The particles are comparatively large and do not get as high into the air as for a surface burst, so that the major portion of the activity returns quickly from the column and cloud to the surface. Deep sub-surface shots deposit almost all of the activity in the ruptured earth surrounding the point of detonation.

Particle size is one of the controlling factors in determining the amount of radioactivity deposited as fall-out, the degree of localization, and the time scale of deposition. The close-in fall-out at an early time after detonation of a surface or underground burst consists almost entirely of the larger particles (above 20 microns in diameter). Small particles, down to and including molecular size, do not tend to fall out early but tend to remain suspended in the upper atmosphere and fall out very slowly. The amount of activity carried per particle is thus an important consideration. One study showed, however, that less than 1% of the fall-out from the JANGLE surface shot was radioactive. It is not known to what extent surface redistribution by the wind affected this measurement.

Various investigations have been made by several laboratories to collect data on the amount of radioactivity which is carried per

particle. These studies show that regardless of the method of sampling or the manner of handling the data, approximately 90% of the radioactivity incorporated in particles is carried by particles larger than 20 microns. A study conducted at UPSHOT-KNOTHOLE[7] indicated that the activity per active particle was approximately a function of particle volume for particles less than 150 microns in diameter and of surface area for particles larger than 150 microns.

C. The Radioactive Cloud.

The release of large amounts of thermal energy that follows the detonation of an atomic device carries the fission product radioactivity by convection high into the atmosphere. The yield of the bomb, the behavior of the fireball in the first few seconds, and the stability of the atmosphere all influence the rise of the cloud and, conversely, the return of the radioactivity to earth.

When an atomic explosion takes place over land, the energy yield is the most important single factor in determining the ultimate cloud height, while the amount of particulate matter from the ground which is contaminated by the burst and carried aloft is determined by the area of the ground contacted by the fireball.

For a contact surface burst, the fireball is roughly hemispherical in shape, and grows to its maximum diameter during the "hover time". The hover time is that interval during which the buoyant forces resulting from the heat of the fireball act to accelerate the fireball and cloud upward. These buoyant forces are essentially independent of the radial forces. After the brief hover period, the fireball leaves the ground and starts to ascend at about five times the acceleration of gravity. After several seconds during which the fireball is rising, the typical mushroom cap and stem are formed. There is a great deal of toroidal motion both in the cap and the stem acting independent of the upward motion, but concurrent with it as shown in Figure 2. At this

7/ Rainey, C.T., Neel, J.W., Mork, H.N., Larson, K.H., Distribution and Characteristics of Fall-out at Distances Greater than Ten Miles from Ground Zero, March and April 1953, WT-811, SECRET Restricted Data.

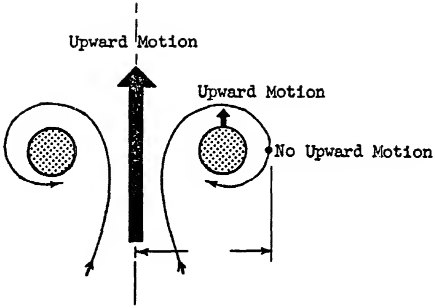

Figure 2. Sketch of a Torus Cloud from a Device After Burst.

time, during the rise of the cloud, the only external force operating against the cloud is that of atmospheric stability. This is of importance since energy is required to sustain the cloud rise, and this energy must come from the thermal energy of the fireball. When the cloud reaches its greatest height, it is said to "stabilize". This occurs at a time when the temperature of the cloud and the temperature of the surrounding air are approximately equal. After stabilization, the mushroom continues to spread, initially because of the kinetic energy remaining after the rise, and later due to diffusion and Brownian motion* of the smaller particles. The time from detonation to the stabilization of an atomic cloud does not vary significantly with yield, but the height and rate of rise vary directly with yield. Figure 3 shows the predicted altitude of the cloud top and between what altitudes the cloud will lie. It will be noted that the cloud base tends to stabilize at the tropopause, a region in the atmosphere, generally at about 50,000 to 60,000 feet

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* Brownian motion: The motion being attributed to the continuous bombardment of the particles by the molecules of the medium in which they are suspended.

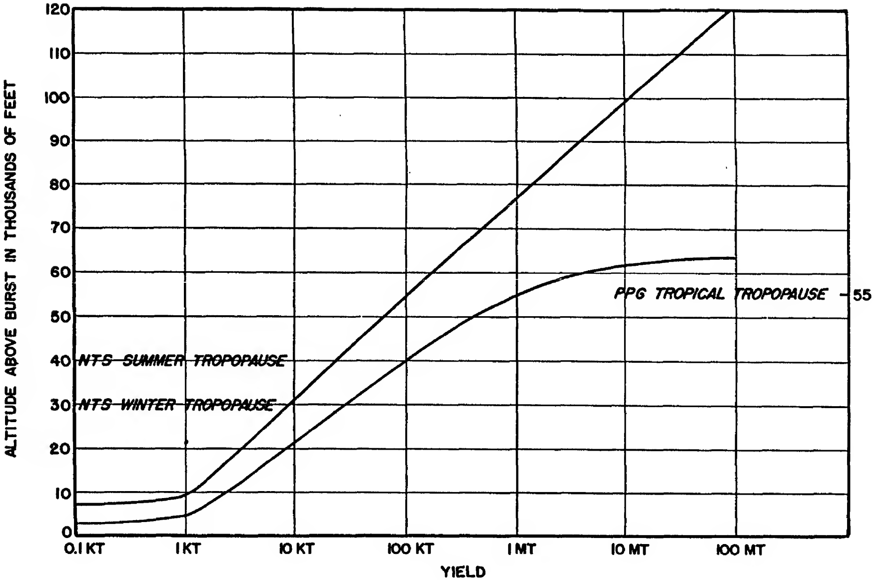

Fig. 3. Cloud Top and Bottom at Time of Stabilization for Various Yield Weapons

characterized by a temperature inversion. Particulate matter on reaching this layer requires more energy to rise further than has been necessary in its previous rise, and can no longer rise on the basis of the negative temperature gradient prevailing up to that layer. If it is assumed that the cloud mushroom contains in excess of 90% of the particles and 90% of fission activity uniformly distributed, then from the available data on world-wide detonations, 36,000 KT has been deposited above the tropopause, while approximately 4,500 KT was deposited below it as the contribution of the 10% of the radioactivity remaining in the stem, and the total activity of stem and mushroom. This takes into consideration the place and date of the known detonations, as well as their fission yields. Since these values are for the clouds at their time of stabilization, they include all the particles that would be found in local fall-out, i.e., those with sufficient weight to be returned to earth within a 50 r infinity dose contour line, plus those which are small enough to be carried outside this contour.

With the stabilized cloud in the air, only two sets of forces can act upon it: (1) atmospheric forces and (2) gravitational forces. The influence of these can be shown by the vector arrows in Figure 4.

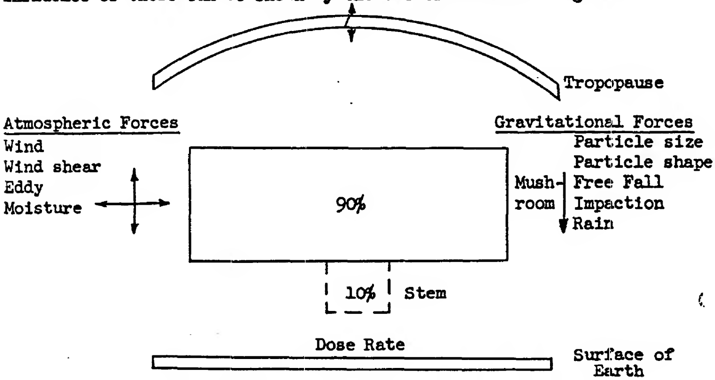

Figure 4. The Atomic Cloud Model and the Forces Exerted Upon It.

For surface detonations, the cloud is generally considered to have about 90% of the activity in the mushroom and 10% in the stem. However, some U.S. investigators estimate a greater proportion of the activity in the stem for surface bursts. The British have estimated 70% in the mushroom and 30% in the stem for their tower shots. This question is presently unresolved; however, the REDWING test series in the spring of 1956 is designed to provide definitive answers. Particles less than 10 microns in diameter are not usually considered of importance in close-in fall-out patterns, since their slow rate of fall would not bring these particles down from the mushroom soon enough to contribute any appreciable activity in the immediate vicinity of the burst point. Instead, such particles are carried by the winds and deposited beyond the local contour system. Once a shape for a cloud model has been agreed upon, then it is reasonable to assume that there is an even distribution of activity, but not necessarily of fission product composition, throughout the cloud. The various horizontal increments of cloud layers or segments will each contain particles of all sizes, but the increments at lower altitudes will contain a higher proportion of heavy particles. This permits the assumption to be made that the "hot spot" ordinarily found close to ground zero results largely from fall-out from the stem or the bottom increment of the mushroom, where heavy particles tend to predominate.

An atomic cloud with the same same general characteristics described in this section forms as a consequence of all ground surface detonations. A high air burst results in a similar mushroom, but the stem is minimal and the large dust cloud that follows the atomic cloud from ground surface bursts is likely to be absent, or if present, strung out as a long ribbon and much reduced in dust content.

For an underwater burst in shallow water, a water column is formed in a manner similar to the dust column formed by an underground burst. The height to which the water column rises increases with the energy of the explosion, and decreases with increasing depth of deton-

ation. As the column falls back into the water, a cloud of mist is formed around the base of the column which spreads rapidly. This cloud of mist, called the base surge, contributes to the spread of the radioactive contamination by moving outward from the base while the column, which is not a true cloud, falls back through the close-in surge into the water. This expanding doughnut-shaped mist appears to carry some activity deposited in it from the column over a greater area than would otherwise be contaminated. The base surge is readily influenced by winds and travels in the direction of the prevailing wind.

An underground burst, described previously, is one in which the center of detonation is below the ground. The mechanism of cloud formation in this case is initiated by the venting of incandescent gases from the fireball directly above the point of detonation. As the gases are released, they carry a large quantity of earth high in the air in the form of a hollow cylindrical column. The material from the crater, much of it contaminated, is thrown out as for a surface burst. As the material in the column cools, the soil particles and entrained air which form the column begin to behave like an aerosol with a density greater than the surrounding air. The column thus falls downward and the finer soil particles attain velocities greater than their terminal velocities in still air. These dust particles spread out radially to form a low dust cloud or base surge similar to that described for an underwater burst. The cloud from an underground burst does not rise as high as for surface or air bursts, and the spread of contamination is thus influenced to a greater extent by lower wind strata. The spread of radioactive contamination is by fall-out from the cloud, the column, and the base surge. As burst depth below the surface is increased, conditions become more favorable for formation of a base surge. More of the radioactive contamination is deposited locally with increased depth, until in the case of no surface venting, all of the contamination is contained in the volume of ruptured earth

surrounding the point of detonation, and no cloud, column, or surge is formed.

D. Effect of Meteorological Conditions on the Cloud.

Four different types of action upon the atomic cloud can result from the winds. When the wind structure is sufficiently large to embrace the whole cloud, gross movement occurs, i.e., the cloud as a whole moves in the direction in which the wind is blowing. When it is just, or very nearly, as large as the cloud, it helps to move it, but tends also to distort it as a whole. When the winds are appreciably smaller scale than the cloud, they cause the cloud to diffuse and lose its shape, because of eddy currents and dilution with clean air. Shear, the fourth action, tends to string out the cloud in ribbons by vertical deformation. The effect of wind shear upon a single radioactive particle that is falling from its position at the time of stabilization is one of lateral translation. The amount of this lateral translation relative to the main axis of travel is a function, within any cloud segment of the wind speed of the segment and the length of time a particle spends falling through that segment. Some of these air movements tend to prolong the time that the large particles are in the air, increasing the horizontal translation by vertical wind motion during the free fall response to gravity.

Particles that range in size from 100 to 5,000 microns are most likely to fall out within local fall-out contours from large yield detonations, although some smaller particles are also found. The particle densities lie within a very narrow range of 2.5 to 2.8 gm/cc for Nevada tests, while at the Pacific Proving Ground they average 2.4 and range from 2.8 to 1.8 gm/cc. When the densities are essentially the same, the free fall rate is a function of particle size and atmospheric density. If constant particle density is assumed, the variation in the rate of fall from different cloud heights can be determined from Figure 5. Evidence indicates that from 50% to 90% of all radioactive particles in a fall-out area are within the size range of 50 to 1,000 microns in

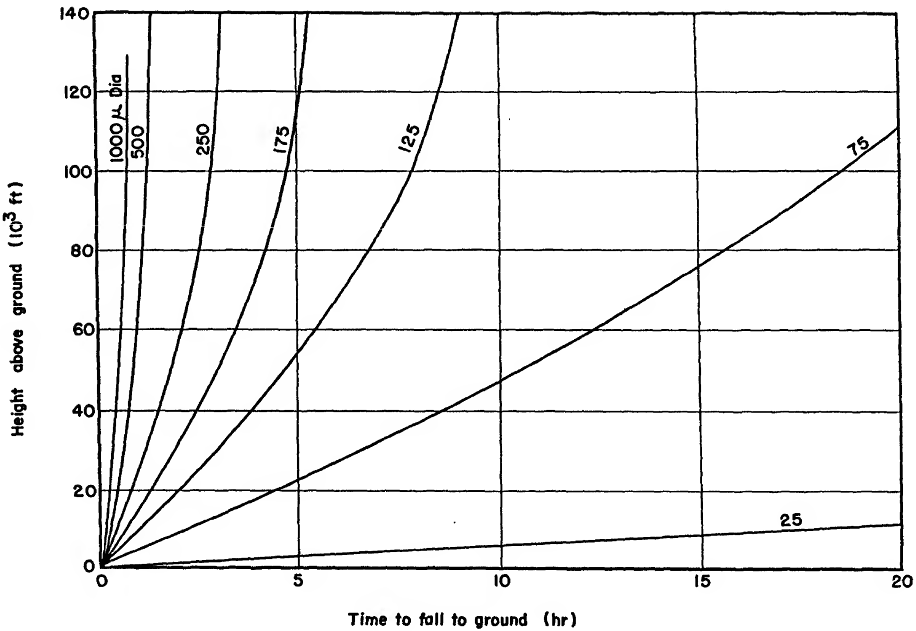

Fig. 5. Time Required for Spherical Particles Having a 2.5 Density and a Certain Diameter to Fall from a Given Altitude to the Ground.

diameter and that from 50% to 90% of the fission product activity is carried by particles of this size range. The influence of atmospheric density can also be noted in the slopes of the curves of Figure 5 in that there is a slower rate of fall as the particle approaches the surface. Spherical particles under 100 microns in diameter thus fall in a manner described by Stokes' Law* with the terminal velocity of those particles in the upper cloud being twice the terminal velocity of free fall in the lower cloud from yields greater than 1 MT. For spherical particles larger than 100 microns, as well as for irregularly-shaped particles of all sizes, free fall is better fitted to a fall described aerodynamically rather than by Stokes' Law. During fall through any one segment or layer of a cloud, the time of fall will be the sum of the time for the loss in height, "gravity", and change in horizontal position, "vertical wind effect". Assuming uniform distribution of the particle size spectrum and of chemical composition throughout the cloud, a projected fall-out field can be made by plotting the time required to travel from the initial placement of certain categories of particles in each cloud segment, to the ground. The activity deposited will vary, owing to the decay of activity in particles composed of very short half-lived elements, individual particle response to wind shear and eddy currents, and redistribution after deposition because of wind and water erosion.

After stabilization, which occurs about 5 to 7 minutes after detonation, the atomic cloud is moved downwind from ground zero. The mushroom having cooled to a temperature about equal to that of the surrounding atmosphere no longer rises, but does expand to a greater diameter. This lateral expansion results from the expenditure of the kinetic energy acquired during the turbulent rise of the fireball, and from diffusion effects. As this lateral growth proceeds, the cloud becomes less sharply defined, and within a matter of hours, except under unusual atmospheric conditions, may no longer be identified visually. The

* Stokes'Law: A mathematical treatment of small spherical particles falling through air in which the viscosity of the air opposes the pull of gravity.

particles at this stage that have not already fallen out are so small as to respond less to gravity than to vertical wind components. Aircraft monitoring has shown the activity at this time to be scattered into wispy patches.

The physical process of diffusion involved in the movement and growth of a cloud results to a large extent from atmospheric turbulence. While little is actually known about diffusion, it results in the spread of clouds of finely divided particulate matter in all directions. The process is not isotropic. Diffusion is thus probably a part of the process by which isolated activity comes to the ground in areas remote from the primary cloud track. After two or three times around the earth, the cloud is diffused to the extent that activity may be collected at many different altitudes. However, airplanes equipped with sampling devices have proved non-uniform distribution of radioactivity by being unable to collect fission product activity on every flight. As the radioactive cloud passes over the earth's surface in this diffused form, portions of its activity continue to be deposited on the ground over periods of weeks and months and perhaps over years. This accounts for the world-wide distribution shown by collection of minute amounts of radioactivity at very remote sampling stations around the globe.

Cloud trajectories have been plotted showing cloud paths from various nuclear detonations. These have been checked for travel more than half way around the world.[8/] The results of aircraft monitoring flights vectored to intersect the cloud met with sufficient success to prove that a nuclear detonation cloud has finite boundaries, radiological if not visual, as much as thousands of miles from the point of origin.

World-wide distribution of bomb contamination has been proven. The key to this distribution lies in the action of world meteorological conditions on diffused and probably dispersed bomb clouds which may

8/ USAF Report of Operation Fitzwilliam (Secret), Nuclear Detonation by Airborne Filters, Vol II, SECRET, Restricted Data.

be weeks, months, or even years old.

The SUNSHINE data, to be discussed later, show the presence of strontium-90 in a significant number of samples taken at many of the far flung net of fall-out collecting stations. Strontium-90 is significant in that it is not a naturally occurring isotope and thus must have originated in an atomic detonation and must have been distributed through the atmosphere by processes such as described above.

E. Mechanisms of Fall-out.

By definition, as used in this report, close-in fall-out is that process by which fission products are returned to earth from a bomb cloud within the isodose line bounding the area within which at least 50 roentgens of radiation would be accumulated if a person remained there in the open indefinitely. Such fall-out generally results from the incorporation of the molecular state radioactive bomb debris in or upon particles that have diameters in excess of 10 to 25 microns. It can be assumed that within a matter of hours only those particles remain in the air that are such as to respond at least equally well to both the gravitational influence of the earth and the vertical air movements that tend to keep them aloft. This aerosol of radioactive particles that is still in the air is not likely to return to earth in appreciable amounts if the particles involved are small enough to be supported by Brownian motion. Association of these light particles with rain droplets is one means by which they are brought to earth. However, rain does not occur above the tropopause so that some other mechanism would have to operate as a scavenging agent if such particles in the stratosphere are to be brought to earth.

When the fireball starts rising after a land surface detonation, any dust or debris that moves with it is available for radioactive particle formation. However, there is other dust, first disturbed by the ground shock and then pulled into the stem by the low pressure region that follows the rapid rise of the cloud, and much of which is subsequently distributed throughout the stabilized cloud. This dust,

although carried aloft, is not heated by the fireball to the temperature necessary for radioactive particle formation, nor is it drawn aloft in time to mix with the fission products to form true radioactive particles. The "dry" scavenging action of these dust particles is known to be very inefficient at low atmospheric levels, and would be even more so at higher altitudes. Thus there is no known scavenging mechanism, except diffusion to the rain-bearing levels, for the very finely divided fission products originally deposited in the stratosphere by large yield weapon detonations.

Rain as a means of bringing radioactive particles to the ground is at least several times more efficient than is dry scavenging. In order to utilize this method, however, the particles must be deposited in the rain-bearing levels -- i.e., below the -15° C isotherm -- or transported to this region by gravitational forces or atmospheric effects. All surface or air bursts with yields in excess of 8 KT result in clouds with the mushroom stabilized above the -15°C isotherm. Thus, rain to be an effective scavenger depends upon efficient deposition of the radioactive particles in rain-bearing levels. An exception to this occurs in the formation of thunderstorms where localized moisture-bearing clouds are sometimes swept to great heights for short periods of time. Clouds from small weapons (less than 5 KT) generally stabilize within the scavenging ability of the rain-out region under the -15°C isotherm. The -15°C isotherm for the North Temperate Zone lies between 15,000 and 20,000 feet, although thunderstorms can rise as high as 55,000 feet and last as much as an hour. Frequency and amount of rain per month or per season are known within limits of useful accuracy for many areas of the world.

The primary mechanism for rain scavenging appears to be fall of raindrops through a volume containing radioactive particles, with entrapment of particles in the falling raindrops. Raindrops are known to vary considerably in size. Since the "collection efficiency" of rain is a function of the rate of fall of the raindrop and the fall of the

radioactive particle, it is thus a function of the densities and diameters.

The second method of rain scavenging which accounts for a smaller fraction of rain-out is the intermingling of an atomic cloud with a rain cloud. The rain cloud in this instance gathers up bomb debris or other contaminated particles into small droplets, which are then collected by large water drops and brought to earth as radioactive rain. This method of cleaning the air is most efficient in particle sizes of about 1 micron but is capable of scavenging any particles that are less than 2 microns in diameter.

The mechanism of particle movement down from the stratosphere and into the troposphere is not understood. In fact, it has not been definitely ascertained whether any of the small size stratospheric bomb debris has come to the ground. Such data, when available, would yield important information concerning the exchange of matter between the stratosphere and the troposphere. One tentative conclusion can be drawn: if particles are so light as to remain in the stratosphere for long periods of time, there is an increased chance of the harmful isotopes being dispersed; hence the reconcentration of these isotopes would be unlikely. It may also be concluded that particles small enough to remain aloft for sufficient time to become a possible long-range threat are too small to be scavenged efficiently by rain when they reach rain-bearing levels.

During thunderstorm formation, the rain cloud is sometimes swept up to the tropopause where the cooled water particles form ice crystals about any small debris or dust that might be in the air. Because the lower atmosphere air is drawn up into the cloud the ice crystals descend and ascend alternately until they become hailstones, or are captured by raindrops, and fall to the ground during a thunderstorm or hail storm. Measurements of radioactivity in large hailstones from a hail storm at Washington, D.C.,[9] following Shot 10 of UPSHOT-KNOTHOLE

9/ List, R.J., The Transport of Atomic Debris from Operation UPSHOT-KNOTHOLE, U.S. Weather Bureau Report, NYO-4602, June 1954, SECRET Restricted Data.

indicated that the greatest activity was in the core, so that the activity must have been picked up early in the cycle of hailstone formation. Another indication of the ability of rain to scavenge at great heights was a fall-out upon Albany, N.Y., from a portion of the cloud which was stabilized at 40,000 feet and not at lower levels. Gummed peper collectors counted 1.6×10^7 disintegrations per minute at Albany following a severe thunderstorm, but the count was low at the six stations near Albany. While not a hazard to health, this disintegration level is very much higher than background. Although thunderstorms are the largest single source of rain in the United States east of the Rocky Mountains, their very limited size geographically and the infrequency of their formation suggest that they do not account for much of the total radioactivity that is returned to earth.

F. Fractionation.

The probability that fractionation exists in a detonation of a nuclear weapon has long been suspected by investigators, and each careful study of the radionuclides formed from detonation of test weapons helps to substantiate the hypothesis. There are several definitions of the term; however, for purposes of this report the one proposed by Stanford Research Institute[10/] that "fractionation can be defined as any variation from the expected value in the relative fission product nuclide abundance" will be used.

The degree of fractionation is a function of the particle size and chemical composition of the vehicle for fall-out, the environment of the particle after fall-out, and the physical and chemical properties of the radioactive elements formed in the fission process as well as those of daughter elements formed in the decay chain. The fission process yields constant relative amounts of radioactive isotopes, depending upon the fissionable material used. The half-lives of the 170 isotopes from 64 known decay chains contribute to the over-all fission

10/ Cadle, R.D., The Effects of Soil, Yield, and Scaled Depth on Contamination from Atomic Bombs, Stanford Research Institute, S.R.I. Project Cu-641, 29 June 1953. SECRET Restricted Data.

product decay constant of $t^{-1.2}$. As previously stated, the average gamma energy of the mixed fission products varies with time, becoming less during the first four days then gradually increasing during the next several days. It might be expected that random gross samples of mixed fission products brought down as fall-out would have about the same decay rate and energy. This is not found to be the case because of the phenomenon of fractionation.

Fractionation depends to a large extent upon volatility, the solubility, and other physical and chemical properties of the fission products, both for the first elements of a decay chain and its subsequent radioactive decay products. When a nuclear weapon is detonated on the ground, the duration of the fireball and the chemical composition of the soil are the predominant factors in determing the composition of the fall-out particle. The larger the weapon and the longer time that heat is evolved in the fireball while it is in close proximity to the ground, the greater will be the effect on early formed products, and particularly on gaseous elements. Fractionation may take place within the fireball of an air burst but the results are not as apparent as for surface detonation fractionation.

When particles fall to the ground, whatever the effect within the fireball, further fractionation is possible, due to the solubility of the specific radioactive isotopes present and their compounds, as well as the characteristics of the soil upon which the fall-out is deposited. Some of the most fruitful studies on the movement of various ions of biological importance through soils have been made by the Waste Disposal Group at the Hanford Atomic Products Operation.[11/] It was found from a study of several elements that movement of ions by the mechanism of adsorption and elution on the soil decreases with increasing acidity. Further investigation revealed that the presence of phosphate ions in

11/ Parker, H.M., Radiological Sciences Department Quarterly Progress Report, Research and Development Activities, Hanford Atomic Products Operation, HW-34408, SECRET Restricted Data.

the soil results in a very markedly increased adsorption of strontium throughout the range of acidity or alkalinity studied. The effect is to make plant uptake of strontium much less likely. This phenomenon will be discussed more fully in a subsequent section on hazard evaluation.

Movement of radioactive particles by wind erosion has been studied by the Hanford Group. This study was designed to investigate particle pickup as well as the relative efficiencies of various surfaces for retaining small particles. Using a 20 foot circular sand plot as the contaminated study area, it was found that the source was seriously depleted following two days of fresh surface winds of 15 to 25 mph, indicating that the natural surface of this particular type of soil is highly erodible and that particles deposited on such a surface are susceptible to subsequent translocation in windy weather. A second experiment was a study of the relative retentive efficiency of grass-covered, rock-covered, furrowed and fence-protected surfaces. Preliminary analysis of the data indicated that rock-covered and grass-covered surfaces retain particles equally well. The furrowed surface retained particles poorly when compared to the grass or rock-covered surfaces. The highest particle retention was observed in the immediate lee of the fence, but this result is somewhat open to question because these areas were shaded from the sun and were noticeably wetter than the other areas.

Both strontium-89 and strontium-90 are examples of radioisotopes having gaseous precursors and are thus subject to a high degree of fractionation. To illustrate the decay chain, the following equations are shown:

$$\text{Krypton-89} \xrightarrow[2.6\ \text{min}]{\beta^-} \text{Rubidium-89} \xrightarrow[15\ \text{min}]{\beta^-} \text{Strontium-89} \xrightarrow[\cancel{53}\ \text{days}\ 55]{\beta^-} \text{Yttrium-89 (stable)}$$

$$\text{Krypton-90} \xrightarrow[33\ \text{sec}]{\beta^-} \text{Rubidium-90} \xrightarrow[\text{V.Short}]{\beta^-} \text{Strontium-90} \xrightarrow[\cancel{25}\ \text{yrs}\ 19.9]{\beta^-} \text{Yttrium-90}$$

$$\xrightarrow[62\ \text{hr}]{\beta^-} \text{Zirconium-90 (stable)}$$

Thus, the duration of the fireball, at which time radioactive particles are being formed, will have a marked effect upon the availability of

strontium-89 or strontium-90 for incorporation into the large particles because of the short half-lives of the parent isotopes. If the fireball is of brief duration, as for low and medium yield weapons, the large particles are cooled when relatively little strontium-89 would be found, with more strontium-90 being available. The smaller particles which stay up a longer period of time and travel long distances can absorb krypton and thus are likely to include more radiostrontium than those particles which fall out immediately. On the other hand, a large yield weapon with a longer lasting fireball may have an appreciable amount of strontium-89 present and a larger proportion of the precursors for strontium-90 would have decayed. Thus, fractionation of strontium due to the decay chain process is apt to be less in large yield detonations than in those of smaller yield. From the data available, fractionation appears to be more extreme for surface shots and underground bursts than for air bursts of the same yield weapons.

Some of the formed radioactive elements that have half-lives of several hours are metals and are found in particles of various sizes in a rather constant percentage of the fission yield, showing little or no tendency to fractionate.[12/] Molybdenum-99 and cerium-144 are examples of this phenomenon. These elements are frequently used as a reference to determine fractionation of other elements. To illustrate this, an equation of the general form

$$R = \frac{A_1/A_2}{(A_1/A_2)c}$$

is used, in which A_1/A_2 is the measured activity for two fission products, the activities having been corrected for decay between time of explosion and time of measurement, and $(A_1A_2)c$ is the activity ratio of the same two fission products measured under the same laboratory condition, but produced by slow neutron irradiation of uranium-235. An R value of unity for the particles analyzed for these two isotopes would indicate no fractionation.

12/ Adams, C.E., et al., Fall-out Phenomenology, Scientific Director's Report Annex 6.4, GREENHOUSE 1951, WT-4, SECRET Restricted Data.

This approach to the problem has been used for studies on detonations in both the Pacific Proving Ground and at the Nevada Test Site. In general, the data indicate that for close-in, early fall-out, fractionation does occur in many instances and is subject to many variations depending upon conditions, such as height of burst, duration of fireball, etc. As expected from the earlier discussion, strontium exhibits very definite fractionation. On one series of air samples collected at 40,000 feet at Operation CASTLE after the Bravo shot, the R value for strontium-89 was 0.35. For a fall-out sample collected on land at approximately 80 miles from the burst point, the R value for strontium-89 was 0.14. The R value for strontium-90 using the same fall-out sample was 0.29. If $\frac{Sr^{90}}{Sr^{89}}$ is calculated, it indicates that $\frac{Sr^{90}}{Sr^{89}} = 2$, or that strontium-90 is less fractionated close-in than strontium-89 by a factor of about 2. Fractionation of this magnitude of strontium means that the quantity remaining in the atmosphere should be greatly increased over the calculated value based on the Hunter-Ballou Tables. The findings of the gum paper experiment of the New York Operations Office, AEC, indicate that this is true and that the discrepancy factor is about 3.

A different approach to this problem was followed at Operation UPSHOT-KNOTHOLE.[13] It was concluded from biological studies on both vegetation and indigenous herbiverous animals that, percentage-wise, more strontium was available at distance of 150 miles than at 20 miles. The strontium-90 at the more distant station was also about four times as available for biological uptake as close-in fall-out. This fact may have been due either to the particle size being smaller and having more strontium-90 present percentage-wise, or that the chemical or physical form was such that the plants could more easily assimilate it.

From the foregoing discussion, there is very little question that

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13 Larson, K.H., et al., Distribution and Characteristics of Fall-out at Distances Greater Than Ten Miles from Ground Zero, UPSHOT-KNOTHOLE WT-811, March-April 1953, SECRET Restricted Data.

fractionation can occur in a number of ways and that environment has considerable effect upon the concentration of various radio-elements of biological importance. The specific importance of fractionation in certain hazard calculations will be discussed in a later section.

G. Areas Involved and Material Available.

The area involved in fall-out resulting from a surface or near surface detonation depends upon the energy yield of the detonation, the height of burst, velocity and direction of winds at all altitudes up to where the mushroom cloud stabilizes, and the type of bomb. As was indicated in a previous section, the yield of fission products, irrespective of the total energy of the weapon, determines the quantity of available radioactive materials which can be deposited as fall-out. Thus. is compared to a weapon with 5 MT fission yield and 5 MT fusion yield, the physical mechanism involved in each case would be approximately the same but the relative intensities of radiation in the area would be considerably higher, possibly by as much as two orders of magnitude, for the 5 MT fission plus 5 MT fusion yield weapon.

After fall-out of radioactive debris occurs, the radiological situation may be ascertained by use of radiac instruments. These may be used on the ground, taking the readings at about 3 feet above the surface, or from a low flying plane at 200 to 500 feet above the surface and applying suitable correction factors which depend on the altitude of measurement and the instrument used. In any event, readings are taken at specific points and plotted on a map at various times following the end of the fall-out. The final situation cannot be known during the period that fall-out is occurring. During fall-out the final radiological situation can only be estimated when the height of burst, the fission yield, the total yield of the weapon, and the wind history since burst time at all altitudes where the cloud has gone, are known. The true situation can be known after fall-out is completed and all readings are made and intensities at specific times after detonations

are known. Calculations can be made to estimate what the reading will be at some future time or was at some selected previous time by using the $t^{-1.2}$ fission product decay law. Figure 6 is a graphical presentation of this law for this purpose. By drawing connecting lines to the points of same intensity readings calculated to the same time-dose-rate relationship, isodose rate lines or contours can be constructed. For planning purposes, before fall-out is completed and the true contour patterns are known, smooth, idealized contours are generally constructed, calculated for some specific time following detonation such as H+1 hour or H+2 days, etc. For this purpose, since the ultimate wind structure is not known at the time the contours are drawn, a basic simplification is made in that a single wind of constant velocity is assumed to act on the bomb cloud. For cases in which the wind shear is not excessive, this approximation does not introduce serious errors. Frequently, isodose contours are also constructed to indicate the integrated dose over a certain period of time, as for example up to H+50 hours.

The family of curves included in Figure 6 is a graphic representation of several H+1 hour radiation dose rates, in roentgens per hour, with time after detonation plotted against dose rate. Using these curves, one can calculate the dose rate at any hour after the burst if the H+1 hour dose rate is known. Also the H+1 hour dose rate can be calculated from the actual measured dose rate at any particular time.

Dose and dose rate contour lines are drawn in such a manner that the boundaries represent the minimum quantity for the area enclosed. An example of a family of idealized contours for a 20 KT land surface burst is presented in Figure 7. The intensity is greatest at some point on the mid-line, becoming gradually less as one proceeds peripherally. Locations of high radiation intensity, or "hot spots" as they are called, are not indicated on most contours. Additional examples of contour areas and downwind extents for an assumed 15 knot wind condition and for a number of different yields are given in Table 1.

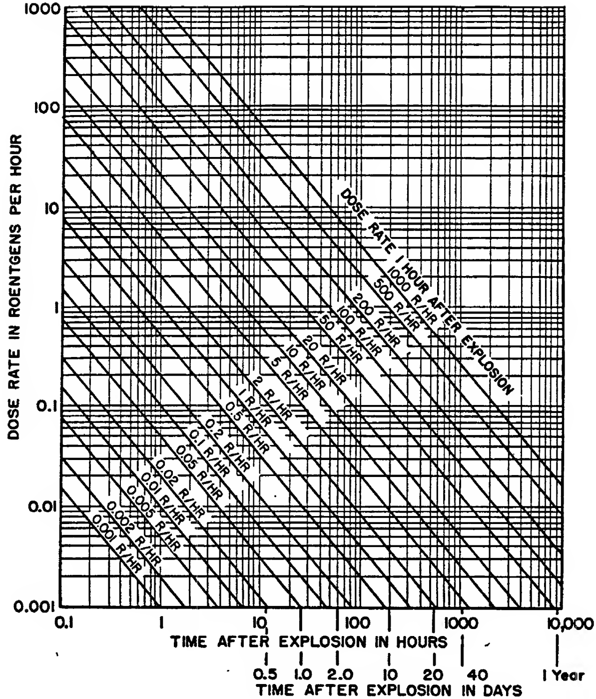

Fig. 6. Dose Rate, Roentgens Per Hour Mixed Fission Products

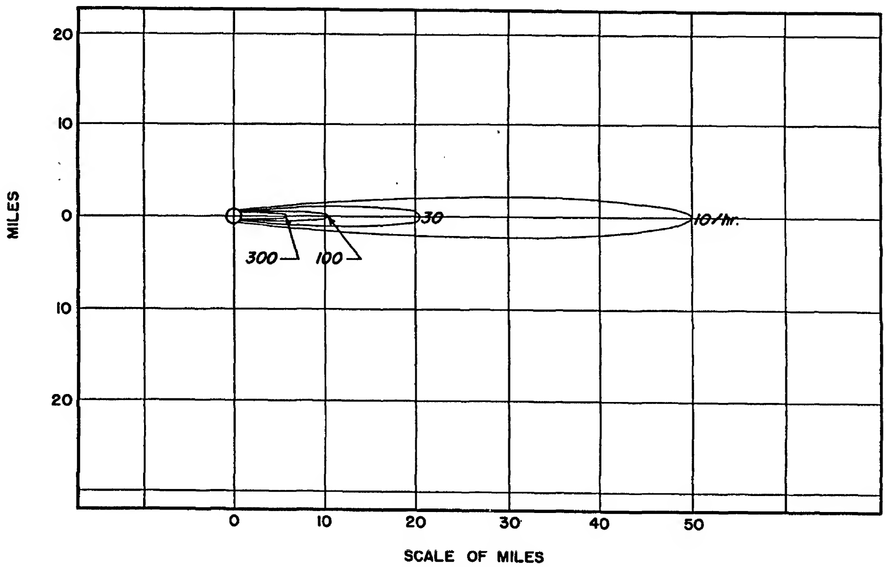

Fig. 7. H+1 Hour Idealized Contour Lines for 20 KT Ground Burst 15 Knot Wind

TABLE 1

H+1 Hour Reference Time Dose Rate Contour Areas
and Downwind Extents for Various Yields
(Surface Burst, 15 Knot Scaling Wind)

Yield	3000 r/hr	1000 r/hr	300 r/hr	100 r/hr
	Areas in Square Miles			
15 KT	0.1	0.5	2.2	8.0
25 KT	0.18	0.9	4.0	14
50 KT	0.4	1.9	8.2	27
100 KT	1.0	4.0	17	55
500 KT	6.0	38	100	450
1 MT	14	70	250	800
5 MT	100	560	1800	5400
10 MT	300	1500	4200	12,000
15 MT	520	2500	7000	20,000
	Downwind Extent from Ground Zero in Miles			
15 KT	0.8	2.0	4.5	9.6
25 KT	1.2	2.7	6.0	13
50 KT	2.0	4.2	9.2	20
100 KT	3.3	7.0	14	30
500 KT	9.5	19	37	70
1 MT	15	29	54	100
5 MT	40	76	140	230
10 MT	62	120	200	330
15 MT	80	150	250	400

For recovery planning, these contour areas are very useful in that times of entry into an area for decontamination or recovery and the time of stay in the area so as not to exceed a predetermined radiation dose can be estimated. However, readings on radiac survey instruments must be relied upon for integrated radiation received during the actual operation, as well as for delineation of the true contour patterns involved.

Figure 8 is a useful plot for facilitating time-of-stay calculations. Perhaps the best way to explain the method of employing this set of curves is to cite an example. Assume that an individual enters a contaminated area 12 hours after detonation and the reading at this time is 5 roentgens per hour. As planned for the operation, it will be necessary to stay in the area 3 hours. Thus, on the horizontal axis, select the time 12 hours, read vertically to the intersection of the 3-hour curved line. Read the vertical axis, as indicated D/R. This value of 2.6 is multiplied by the radiation intensity, 5 r per hour, to give 13, which is the total number of roentgens received during the period of the stay in the area.

The scaling of residual radiation contours is not a simple process because of the many variables involved. In addition, changes in cloud models and in mechanisms of deposition occur with changes in yield and in wind velocity. For example, the tropopause layer in the atmosphere has a slowing down effect on the rise of an atomic cloud through it, with the result that atomic clouds which reach this layer tend to flatten out against it, as though against a ceiling. The result is that such clouds are broader, and their fall-out deposition patterns are wider and shorter, than would be the case from an identical detonation whose cloud did not reach the tropopause. A valid and ideally useful scaling process should be easy to apply and should be based on a conservation of material assumption, since it is obvious that the scaling process should not cause more material to fall out than is available. One such method is "cube root scaling", by which linear contour dimensions are scaled as the cube root of the ratio of yields and areas as the two-thirds power of the ratio of yields, with simultaneous scaling of contour dose rate values as the cube root of the yield ratio. This method conserves material, in that the percentage of available material brought down within each scaled contour remains constant. It is also easy to apply. However, it is subject to the inherent inaccuracy discussed above and common to all residual radiation scaling methods developed so far: it does not allow for the changes

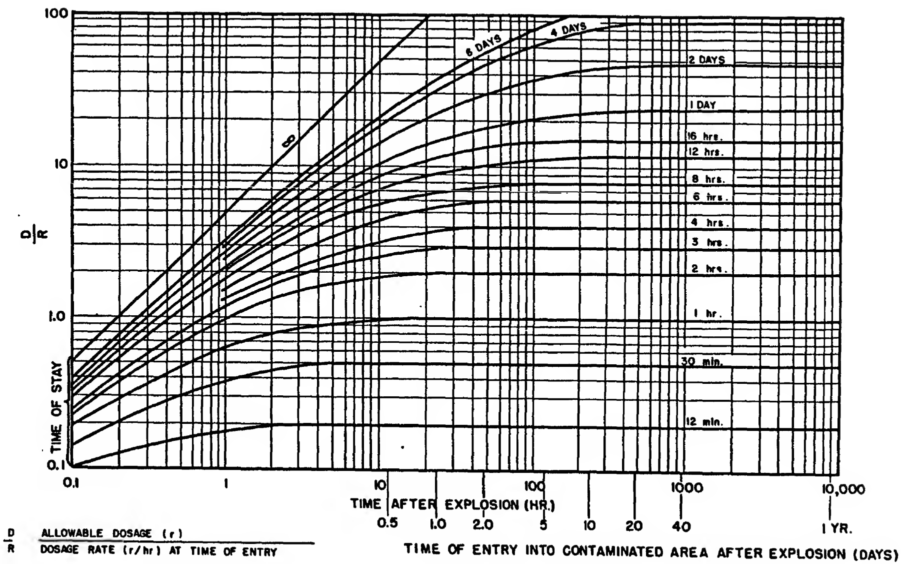

Fig. 8. Dosage Received with Various Times of Stay in Contaminated Area

in cloud models and deposition mechanisms that are introduced by a change in yield. Nevertheless, the method is useful and fairly accurate if applied over a limited yield range, not to exceed about two orders of magnitude.

Wind velocity scaling is even more subject to error than is yield scaling. Based upon limited high explosive experimental data, using dye tracers, it has been postulated that total areas of effect of fall-out for a particular detonation are essentially wind-independent, although the specific regions which these areas cover are of course determined in detail by the wind pattern. The experimental data extends only to winds up to 25 knots; however, in the absence of other information, extrapolation to higher wind velocities is not unreasonable. On this basis, then, contour dimensions in a downwind direction would be scaled in direct proportion to the cube root of the ratio of the winds involved, while crosswind dimensions would be scaled inversely by the same factor, leaving the area of effect essentially constant.

The effect of winds upon the direction of the fall-out and the area involved can be shown graphically by setting forth certain assumed meteorological conditions. One example of such assumptions is presented in Figure 9. Superimposed upon the wind vector plot is a family of idealized isodose contour lines for a 20 KT ground burst. It will be noted that the shaded area, which is due to diffusion, and the A", B" ..... F" due to 50 micron particles, do not contribute appreciably to the radiation intensity within the area. The highest radiation readings in the contour areas are close in to the burst point and the radioactivity deposited there is carried by the larger particles. For purposes of the illustration, the size assumed for the large particles was 150 microns and the greatest effect by the wind is indicated on the line A', B' ..... F'. The area covered by superweapon detonations would be much larger and wind shears at high altitude would have a greater effect upon the true pattern, but the method of illustration is the same. Such a superposition is useful in indicating where the

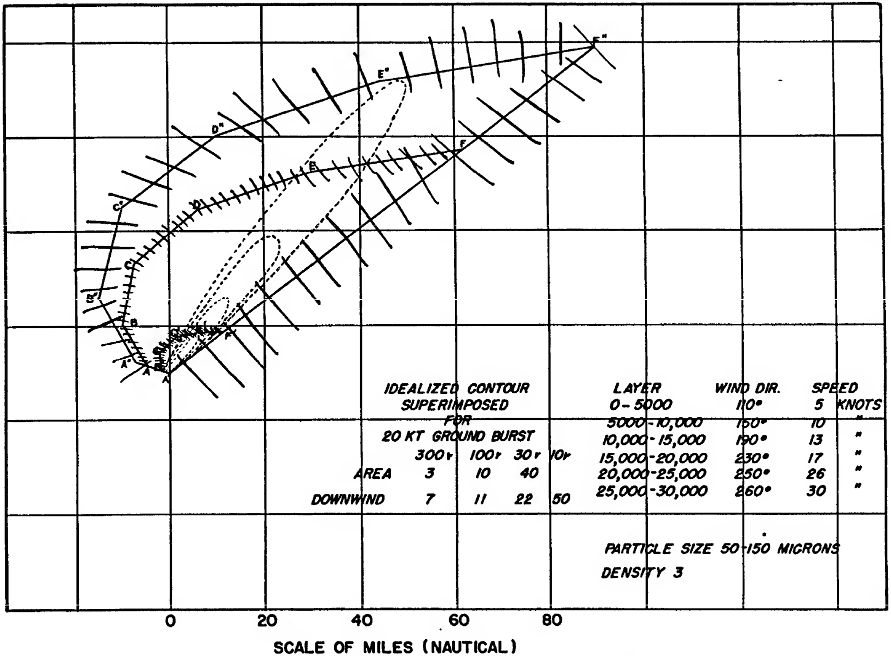

Fig. 9. Wind Effects on Fall-out Pattern, with Superimposed Idealized Contour

true fall-out pattern is likely to deviate from the idealized contours.

The total dose accumulated by an individual in a fall-out field varies with the time of entry. For example, a reading of 50 r per hour in an area taken 30 minutes post detonation will decrease to 22 r/hr at one hour. If an individual remains in this area during the period between H+30 minutes and H+1 hour, he will accumulate a dose of 16 roentgens. If a reading is 50 r/hr at one hour and he enters at H+1 hour and stays 30 minutes, he will accumulate 20 roentgens. This difference at an early time post detonation is characteristic of the rapid decay of a fission product field at early times. However, in another area with a reading of 50 r/hr at H+8 hours and a stay of 30 minutes, an individual will accumulate a dose of 24 roentgens. Thus, at later times with the same reading in roentgens per hour, a larger amount of radiation is accumulated for the same time of stay.

The variation of the energy spectrum with time has been the subject of field evaluations at several test operations. It was found at CASTLE[14/] that a considerable fraction of the gamma energy in fall-out is in the vicinity of 0.1 Mev. After 10 days there is an accentuation in the regions of 0.5 Mev and 1.6 Mev. This is attributed to the Ba^{140} - La^{140} radiations. As this decreases a concentration of the spectrum in the 0.7 Mev region is noted.

The military situation requires a more detailed discussion of the immediate fall-out area for a surface burst and the area around ground zero for air bursts. The radiological problems encountered in these two areas will exert a strong influence on decisions for weapon employment, as well as on deployment of troops and exploiting the advantages of the use of nuclear weapons.

Following an air burst, no radiological fall-out of consequence will be encountered. The dust swept up into the cloud from the blast effect on the ground will fall out within a short period of time. How-

14/ Cook, C.S., Fall-out Symposium (Confidential), Armed Forces Special Weapons Project, AFSWP-895, SECRET Restricted Data.

ever, dirt is an exceedingly poor scavenger for small radioactive particles which would be found in the mushroom cloud of an air burst, so that even though soil particles and the cloud intermingle, it does not follow that significant radioactivity due to fission products will be present in the immediate fall-out. As noted in a previous section, however, neutron induced activity in the soil near ground zero can result in dangerous gamma ray intensities for certain high neutron flux weapons burst over certain soils.

On the other hand, a different radiological situation will be found for surface or near-surface detonations with the fireball on the ground or near enough to the ground so that soil particles will be swept up and reach a temperature that will allow radioactive fission products to be fused into or adhere to the particle. Inasmuch as the isodose rate contours resulting from such bursts have been discussed, only the influence of induced activity in bomb debris will be mentioned. The primary effect is the introduction of small perturbations in the $t^{-1.2}$ decay curve from about H+10 hours to H+10 days. The radioactive decay of soil samples collected at Operation CASTLE at the Pacific Proving Ground is shown in Figure 10. The influence of the neptunium formed from the capture of neutrons by uranium-238 is noted by the slight curve on what would otherwise be a straight line. The beta energy of neptunium-239 is slightly higher than for many fission product mixtures so that high concentrations of the element in a sample will change the average beta energy for the sample.

There is a marked effect by terrain on actual radiation intensities received. The radiation intensity above a completely smooth contaminated plane is easy to calculate. However, a rough terrain permits the radioactive particles of fall-out to be more highly concentrated in some spots than others, as well as affording some degree of shielding. Many of the particles could fall where very little radiation effect would be seen but at the same time hot spots could occur in certain depressions in the terrain. This could be more hazardous than indicated

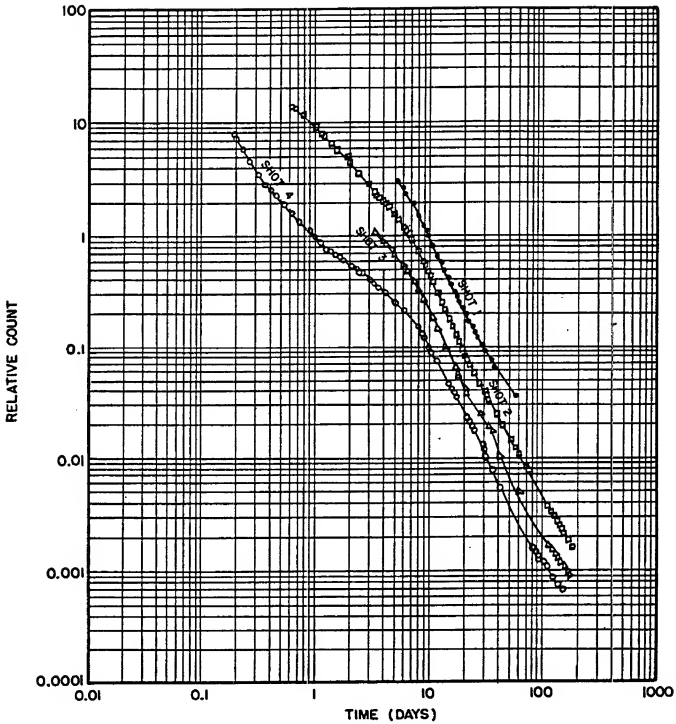

Fig. 10. Gross Gamma-Ray Decay of Fall-out Samples from CASTLE Shots 1, 2, 3, and 4

by the average reading on a radiac instrument. One such example would be a ditch in an area with a surface wind of sufficient intensity to blow particles into such depressions after the initial deposition of fall-out. Troops using these depressions for protection might be exposed to more external gamma radiation than a meter in the open would indicate. The beta activity in such depressions would also be relatively higher. If the fall-out occurred on a sea area, for example, while troops are being transported on ships, the ships would be the primary areas of high levels of radiation. Fall-out material falling into the water is somewhat soluble and in addition the majority of the particles tend to settle with sufficient rapidity to decrease the radiation intensity to a non-hazardous level within a short time, whereas the same amount of activity deposited on a land surface could be very hazardous.

A discussion of the biological effects of radiation from a fall-out area will be given in the section on hazard evaluation. Suffice it to say here that knowledge of isodose contours aids materially in the evaluation. Further discussion of the world-wide fall-out situation will be given in other sections of this report.

The height of burst above the surface of the ground has a marked effect upon the percentage of expected fall-out from a true surface burst. In previous examples, only contact ground bursts were considered. As a rough rule of thumb, the percentage of total fall-out available that is deposited within local contours is about the same as the percentage of fireball volume subtended by the earth. Thus, for a contact surface burst, roughly 50% of the available fission product activity is deposited within localized contours. Figure 11 indicates the relative degree of contamination to be expected from near-surface bursts as compared to contact surface bursts. The general shape of the fall-out pattern is seen to be approximately the same for a burst very close to the surface as for a surface burst, but the level of activity is different by the percentage indicated. Table 2 has been

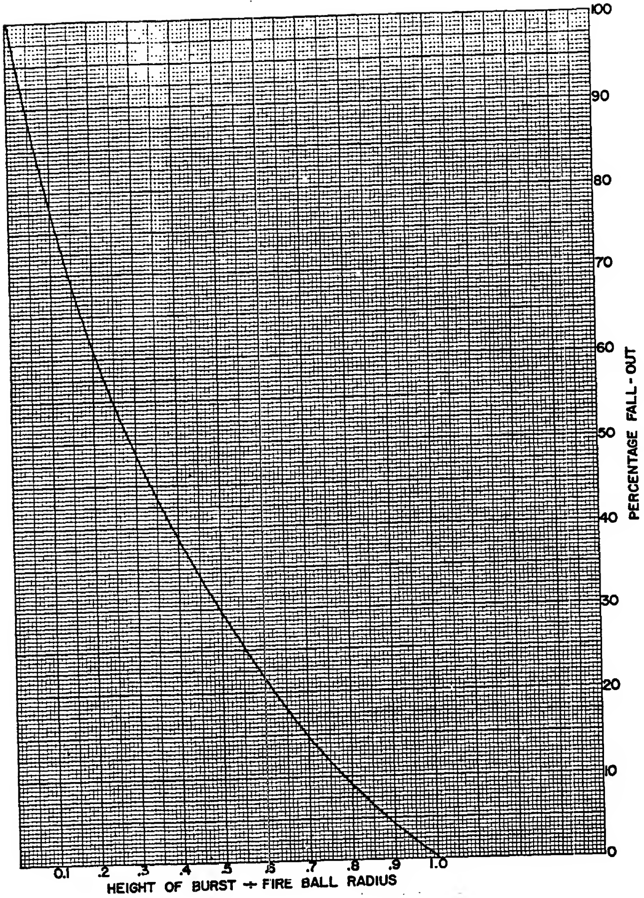

Fig. 11. Percentage of Fall-out Expected from a Near-surface Burst Normalized to a Surface Burst

developed from Figure 10 for six different yield weapons and for two different burst heights above the ground and indicates the percentage of fall-out to be expected in these cases.

TABLE 2

Yield	Ht.of Burst (feet)	Radius of Fireball (ft)	Height of Burst / Radius of Fireball	% Fall-out Relative to That From a Surface Burst
1 KT	50	180	.28	50
1 KT	100	180	.56	25
5 KT	50	340	.15	67
5 KT	100	340	.30	48
10 KT	50	460	.11	75
10 KT	100	460	.22	57
50 KT	50	870	.06	86
50 KT	100	870	.12	73
500 KT	50	2200	.02	95
500 KT	100	2200	.05	89
1000 KT	50	2900	.02	95
1000 KT	100	2900	.03	93

An uncertainty of great potential importance exists in the current state of knowledge regarding the maximum dose rate intensities that are likely to be encountered on the ground following a true land surface burst. This uncertainty exists because only one nuclear detonation has occurred thus far on a true land surface, and this one experience was for the relatively low yield of 1.2 kilotons at Operation JANGLE. A crater and lip dose rate of 7500 r/hr at H+1 hour was recorded after this shot. Although scaling laws would predict an increase in crater and lip dose rates with increase in yield, such higher dose rates have not been observed following the large yield surface detonations at IVY and at CASTLE; instead, the highest well substantiated dose rate readings at 1 hour after burst for any of these shots appear to lie in the range of 5,000 to 10,000 r/hr. Some have theorized that this is due to the fact that the crater lips have been washed by waves and that the

craters themselves have filled with water following the surface bursts in the Pacific, and thus hold that a true land burst would give higher crater intensities; others contend that the deposition mechanisms change with yield, so that the increased scouring effect and higher cloud rise of large yield weapons would tend to keep the crater and lip dose rates at H+1 hour more or less constant with yield. A firm resolution of this uncertainty is not likely until a test detonation of a medium or large yield weapon is held on a truly representative dry land surface.

The time of arrival of fall-out particles of various sizes from atomic clouds can be estimated using Figure 3, which gives cloud heights, in conjunction with Figure 5, which gives the times for particles of various representative surface burst weapons with yields between 1 KT and 500 KT. The 1000 micron size is probably representative of early fall-out arrival, mainly in the area near the burst point; while the 75 micron size is representative of the fall-out likely to occur in the downwind extremes of the elliptical patterns.

TABLE 3

Total Yield	Cloud Bottom (ft)	Cloud Top(ft)	Bottom of Cloud 1000 μ	Bottom of Cloud 175 μ	Bottom of Cloud 75 μ	Top of Cloud 1000 μ	Top of Cloud 175 μ	Top of Cloud 75 μ
1 KT	4,000	9,000	15min	30min	90 min	15 min	60 min	150 min
5 KT	15,000	24,000	15 "	75 "	180 "	30 "	90 "	300 "
10 KT	20,500	31,000	20 "	90 "	300 "	40 "	120 "	420 "
100 KT	39,000	54,000	45 "	150 "	480 "	50 "	180 "	700 "
500 KT	51,000	70,000	55 "	160 "	650 "	60 "	210 "	850 "

In evaluating the data presented and the material discussed on the problem of the areas involved in close-in fall-out, it must be remembered that most of the information has been gathered from controlled field test operations. Winds at all altitudes were known to the best of the ability of the meteorologists and shot days were selected so that the best conditions existed to minimize the hazard from close-in fall-out. Uncertainties in the information presented are due primarily to the question as to whether the burst conditions under which the test

data were obtained are truly representations of likely operational conditions, and to the difficulties involved in collecting an adequate number of samples at enough points to give a good degree of statistical reliability. The only surface test detonations of major operational significance thus far have been made in the Pacific Proving Ground, where the amount of land surface available and the character of the soil involved are not representative of likely employment conditions to be met in the operational use of nuclear weapons. Many of the uncertainties which now exist could be resolved if the opportunity is ever presented to have a true, large yield land-surface detonation. These gaps in the current fund of knowledge are not considered sufficient to change the basic ideas presented here but only to provide refinements necessary to give a better understanding of the potentialties involved.

H. Evaluation of Fall-out Models.

A fall-out model is a graphical representation capable of utilizing available information to predict the perimeters of the local area that is likely to involve a residual radiation hazard to health following the detonation of an atomic device. Ideally, it should predict with maximum accuracy from a minimum of information and be workable in the least possible time before or after the device is detonated. At present, some of the various models under development are used to insure the continuity of the health and security of the personnel and animals of the two nuclear weapon test sites and their surrounding communities. The predictions of any of the methods can be checked by survey and sampling, and the degree of reliability determined for its practical use in denying areas of danger following a hostile detonation. At Nevada, local fall-out has accounted for approximately 10% to 20% of the fission yield of low tower shots. With the super weapons tested at the Pacific Proving Ground, local fall-out accounts for as much as 50% of the fission products found and encompasses whole island groups.

There have been several models developed either for laboratory reference or for test control conditions. They have been assessed recently by the Armed Forces Special Weapons Project[15] and the summation of the various fall-out models is presented here in its entirety from that report:

Armed Forces Special Weapons Project Method

This method is based on ground surveys at JANGLE (surface) and CASTLE Bravo, and consists of "idealized" contours which follow a single scaling wind direction. Abrupt wind shears and unusual weather conditions are not easily handled. The method is suitable for planning purposes only, not for post-shot analysis. An order-of-magnitude contour can be drawn for any weapon yield between 0.1 KT and 100 MT in two or three minutes by trained personnel.

Air Research and Development Command Method

The model assumes that 90% of the bomb debris activity is in the stem of the stabilized cloud, and 10% is in the mushroom. Mean effective particle sizes are assumed for the cloud and parts of the stem, and Stokes' law fall rates for spherical particles are used. Wind and weather conditions are allowed for. The method is calibrated to CASTLE Bravo, but is adaptable over a wide range of yields. A problem solution requires several hours by trained personnel.

Army Signal Corps Method

The model divides a hypothetical stabilized bomb cloud consisting of superposed cylinders into disc or cylindrical wafers or compartments, each associated with a particular particle size category and fall rate. Each disc is then brought to the ground according to the winds acting on it, and ground values are then summed over all the discs to obtain contours. A different model must be generated for each weapon yield, and for different localities:

15/ Armed Forces Special Weapons Project, Fall-out Symposium (Confidential) AFSWP-895, January 1955, SECRET Restricted Data

tropical, polar, etc. Wind and weather conditions are allowed for. A particle size distribution hypothesized by the RAND Corporation is used. Aerodynamic particle fall rates are used. The method is calibrated to the AFSWP-507 reported survey of CASTLE Bravo. Because of the finite number of discs in the model, contours are often lumpy and may involve artifact "hot spots". A problem solution requires several hours by trained personnel.

Air Weather Service Method

The method is essentially a radex plot resulting in rough sectors within which fall-out may be expected, together with estimated times of arrival along vectors from ground zero for particular altitudes from which it is assumed particles start their fall. The method does not generate contours, and thus is not directly comparable to methods that do. The plot can be drawn in about 15 minutes by trained personnel.

Los Alamos Method

The method was devised for use during CASTLE in forecasting the gross results to be expected from surface bursts of about 10 MT fired in the northern Marshalls. The plots are modified only by direct yield dependence. The effect of yield on initial cloud geometry is not included, nor is the effect of the different tropopause height of the middle latitudes from that in the Marshalls. The method gives very little detail anywhere and none at all near the origin. It is not intended for use in detailed post-shot analysis, but rather for radsafe planning. A problem solution probably requires about an hour for an individual familiar with the method.

Navy Method

This method, which is based largely upon a radex wind plot, is a system of weighing incremental square areas according to the degree of fall-out expected, relative to one another. It results

in wind-sensitive contours which have only relative values. Actual values may be fitted to the contours as a result of one or more post-shot survey readings taken in the contaminated area. A problem solution requires something more than an hour for personnel familiar with the method.

U.S. Naval Radiological Defense Laboratory Method

This is a wind and weather dependent system which assumes the bulk of the radioactive material originates in the lower portion of the mushroom, and utilizes an aerodynamic particle fall rate which varies considerably with the altitude of the particle. A problem solution requires several hours by personnel familiar with the method.

The RAND Corporation Method

The method gives wind and weather-sensitive contours, based on an assumed particle size distribution and the hypothesis that 90% of the fission product radioactivity falls out from the mushroom cloud and 10% from the stem. An aerodynamic rate of fall is used which is somewhat different from that used by NRDL, but which also varies markedly with altitude. A problem solution requires a great amount of hand calculation. The method has also been programmed for machine solution.

Technical Operations, Inc. Method

The method utilizes an inverted cone cloud model, the NRDL assumption of particle size distribution, and fall rates which increase with increase in altitude. A problem solution requires somewhat more than an hour, utilizing trained personnel.

There are two general categories into which the fall-out models can be placed. The first category is that of a rough approximation which will furnish Military or Civil Defense officials with a knowledge of the approximate direction and area of the fall-out field from an estimate of the yield and winds. Such methods must be amenable to

rapid calculation and ease of plotting, as well as involving an acceptable degree of accuracy. The model of the Armed Forces Special Weapons Project is probably the best of this type, basically using a conservation of material scaling approach, i.e., it assumes that a fixed percentage of material will fall out from all shots. As the yield is increased, the sizes of the contours are correspondingly increased. The Navy method is considered second in usefulness for this purpose to the AFSWP method, its main difficulty being its dependence upon an initial survey reading or series of readings made post-shot. If this normalization reading is in error, the entire plot is erroneous. The methods developed by the Air Weather Service and the Los Alamos Scientific Laboratory also fall into this category, the former furnishing little more than direction and time-of-arrival, and the latter having particular application to the radsafe problem.

The second use to which fall-out models are put is that of post-shot analysis. For this purpose, the information must be as accurate as can be obtained and the yield, height of the stabilized cloud, and exact wind history at all levels for the duration of the fall-out period must be utilized. The contours so calculated are then compared in detail with accurate survey data of the area of the fall-out fields and the intensity within the field. The RAND model, used in conjunction with an electronic computer programmed to handle the voluminous calculations involved, appears to furnish the most accurate analysis of the mechanisms and patterns of fall-out deposition at the detonations studies. Much of the information used in describing atomic cloud behavior, particle distribution and meteorological action on the cloud and quoted in this report was also used in the preparation of the RAND model. The Naval Radiological Defense Laboratory is considered second to the RAND model in supplying useful post-test data largely because it has not yet been programmed for a computer. The large amount of manual calculation made necessary in using the NRDL method makes the RAND method preferable. The Army Signal Corps has a useful and fairly accu-

rate method for analyzing fall-out patterns from surface burst 15 MT yield weapons. The method should be modified to permit scaling to other yields and programmed for an electronic computer to make it useful for military analysis. This is the method the Chief of Staff, U.S. Air Force recommended be considered by the AFSWP in the preparation of this study, in a memorandum for the Joint Chiefs of Staff dated 22 June 1955.[16] The Air Research and Development Command method and the Technical Operations Inc. models are also in this post-shot analysis category, and appear to give somewhat less accurate results than the other methods for an equivalent expenditure of computational effort.

I. World-wide Distribution.

Close-in fall-out, as previously defined, is that fall-out within an isodose line which marks the boundary of the area within which the dose accumulated to infinite time is 50 roentgens or more for fully exposed personnel. This area is bounded for a considerable distance by gradually decreasing amounts resulting from fall-out from the primary cloud. The cloud gradually spreads over a very large area and diffuses to such an extent that it is no longer a single entity but may be a series of ribbons several miles wide and hundreds of miles long. These cloud sections continue to diffuse and follow the wind patterns to such an extent that measurable distributions may be found continent-wide for smaller shots and world-wide for large yield detonations. After several months the distribution for all intents and purposes can be considered uniformly spread over the upper atmosphere, but not necessarily uniform to the top of the stratosphere. Thus, world-wide fall-out decreases in deposition rate after reaching a post-detonation peak, but probably does not reach zero as long as radioactive material is present in the atmosphere at any altitude.

The external level of radiation from world-wide fall-out is not a biological hazard. However, the beta particles from internally deposited radioactive material are of considerable biological importance.

16 J.C.S. 1716/18

This is because the low penetrating power of the beta radiation results in the absorption of almost all of the ionizing radiation in tissue within a few millimeters of the particle. It is this low level chronic radiation that is considered as a possible carcinogen.

Part of the bomb debris within the mushroom cloud of large yield detonations goes to a very high altitude and is considered to be deposited in the stratosphere. Another portion of the debris from a large yield detonation, and essentially all of the debris from many low yield weapons, is deposited in the troposphere. Particles initially deposited in the stratosphere and large enough to be affected by gravitational attraction to the earth go from the stratosphere to the troposphere through the atmospheric layer known as the tropopause. However, there is no known mechanism for moving particles of molecular dimensions and only slightly larger from the stratosphere to the troposphere. Several dust samples at altitudes up to 90,000 feet have been collected by the Health and Safety Laboratory of the New York Operations Office of the Atomic Energy Commission following test operations in the Pacific Proving Ground, the collections being made during the summer of 1954. The data indicate inconsistent variation, or non-uniform mixing, at altitudes from 80,000 to 90,000 feet. Values of 0.025 to 0.56 disintegrations per minute per cubic meter of air were obtained of which 0.7% to 4.7% was due to strontium-90. Samples collected at 40,000 feet by jet aircraft showed considerable variation, with only samplers on the right and left wings of a particular aircraft showing consistent results. There was a change from flight to flight on the same day in the same area, but the consistent results from right to left wing of the jet indicated a real variation in total radioactivity through which the aircraft flew. These values ranged from 0.021 to 3.2 disintegrations per minute per cubic meter of air. Although the methods of sampling at 90,000 feet differed from those at 40,000 feet, the results indicate that there is about the same order of magnitude of radioactivity at the two levels, with the radiation levels being slightly higher at 40,000 feet.

An interesting observation was made independently by a British group during the summer of 1954 in flying aircraft over England at [redacted]

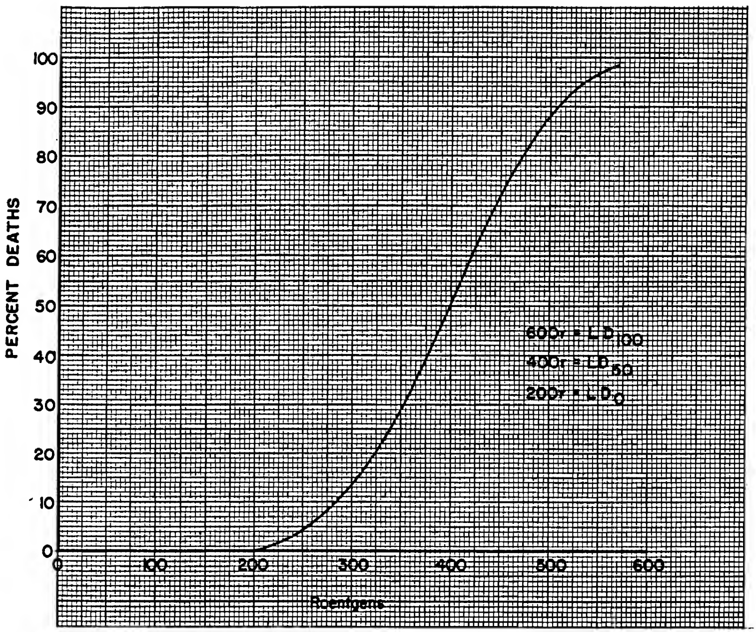

Fig. 12. Lethality vs Dose in Roentgens

fall-out studies were conducted, it was thought that the dose required to cause lethality in 50% of exposed individuals within 30 days - hereinafter abbreviated as LD_{50} - should perhaps be somewhat greater than indicated in Figure 12. After the CASTLE fall-out studies, however, the possibility that the curve values may be somewhat high was raised. The biological effectiveness of radiations from various sources as well as the geometry of both source and receiver are important. Considering the present state of uncertainty regarding each of the parameters involved, it is considered that the original curve should be accepted as it is. One should be conservative with regard to raising the values needed to cause a particular per cent lethality.

Radiation exposure in a fall-out field is not instantaneous. It is therefore necessary to evaluate various time-dose relationships in terms of lethal effectiveness. Protraction and fractionation of a given dose of radiation reduces the lethal effectiveness to a limiting value determined by the non-recoverable fraction of total dose.

In evaluating the lethal effect of exposure to intermittent or continuous radiation over a period of time, the term "effective roentgen" will be used. This means that any time-dose relationship under consideration will be referred back to its equivalent effect on the instantaneous effect curve and the dose will be said to be equivalent to so many instantaneous roentgens. For example, if 600 r are given over a period of time so that 50% of the exposed group can be expected to die, the effective roentgen value will be 400 r.

The decrease in lethal expectancy associated with protraction of the dose delivery period is due to the fact that the body recovers, at least partially, from the effects of a given exposure. This biological recovery factor has been experimentally examined in lower animals. According to E. H. Smith,[18/] the recovery rate for all animals studied may be taken to be 29% per day. The design of the experiments was such that results were not sensitive to this parameter. F. McLean,

18/ Smith, E.H., Informal Study for the Chief, AFSWP, 1953.

[19] writing in the Military Surgeon, has used a factor of 10% per day recovery for a 20-day period, and according to him this scheme breaks down beyond this point.

Although some biological recovery certainly takes place, there is also a degree of permanent residual damage from which an animal never recovers, or at best recovers at a rate so slow as to be difficult to measure. From a quantitative point of view, 20% of the total incident gamma radiation received is considered to be an irreparable equivalent and 80% to be reparable according to the factors given above, i.e., 29% per day by E. H. Smith and 10% per day by F. McLean.

A quantitative approach to lethality estimates may be made by using the following:

(1) Instantaneous lethal curve, such as Figure 12.

(2) Total dose and rate of administration.

(3) Biological recovery rate, using 10% per day and assuming a first order recovery process.

(4) Irreparable recovery fraction, using 20% of total gamma dosage.

(5) Fission product decay law, $I_t = I_1 t^{-1.2}$, where

I_t = radiation dose rate at time t

I_1 = radiation dose rate at unit time

t = time

The final equation in a fission product fall-out field then becomes[20]

$$\frac{R_{eff}(t)}{r(t_o)} = t_o \left[1 - \left(\frac{t_o}{t} \right)^{0.2} \right] + 0.8 t_o^{1.2} e^{-\beta t} \int_{t_o}^{t} \frac{e^{\beta t}}{t^{1.2}} \, dt.$$

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[19] McLean, F.C., et al., Extension to Man of Experimental Whole-Body Irradiation Studies. Some Military and Civil Defense Considerations, Military Surgeon 112, 1953.

[20] Latter, A.L., The RAND Corp., Feb. 1955, Personal communication.

where

R_{eff} = amount of instantaneous radiation required to give the same effect on lethal scale.

(t) = Time of evaluation of R_{eff}.

$r(t_0)$ = Rate at time (t_0) of initiation of exposure.

β = recovery constant, here assumed to be 10% per day or 0.0042 per hour.

Figure 13 is a graphic representation of the above equation for various times of entry into a fall-out field (t_0) up to 19 hours.

This scheme for calculating lethality expectation must be used with caution, and must be restricted to the job it is intended to perform. It will be noted that beyond a certain time the effective roentgen value decreases. This is not intended to signify that the individual is able to continue receiving radiation without further damage. It does signify that for a given radiation experience there is a maximum R_{eff} at which point additional radiation will have its maximal significance with regard to acute lethal effect. It also signifies that beyond the point of maximum R_{eff} the amount of additional radiation needed to produce a given acute lethal effect does increase. The aspect of damage to the individual which is a function of the total dose continues to increase during the period of radiation beyond the point of maximum R_{eff}. In a real sense, therefore, the biological damage factor is a function of the total irreparable dose and the R_{eff} is an index relating lethality expectation of further radiation to the past radiation experience of the individual. However, it should not be overlooked that R_{eff} is bounded by the lethal dose, and that once this dose is reached, biological recovery factors no longer play a role, nor does additional radiation have significance.

Figure 14 is a graphic representation of a fall-out situation occurring at H+3 hours with an initial dose rate of 40 r/hr leading to a total integrated dose of 600 r which would be LD_{100} if received instantaneously. The upper broken line indicates the cumulative dose

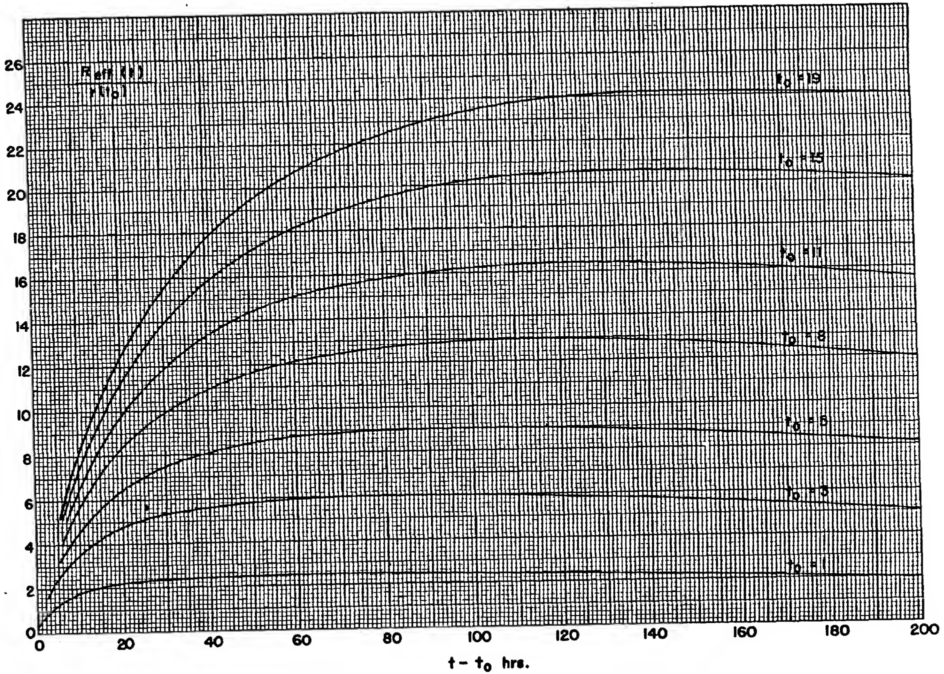

Fig. 13. A Graphic Representation of the R_{eff} Equation for Times (t_o) Up to 19 Hours

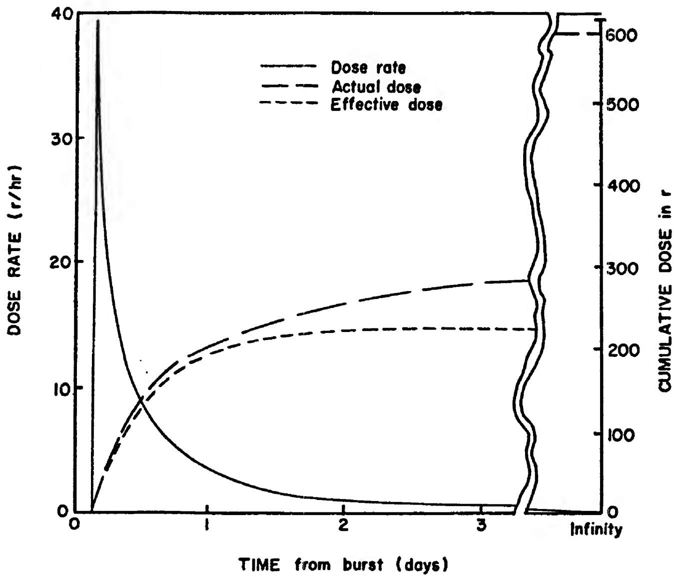

Fig. 14. Graphic Analysis of H+3 Hour Fall-out Situation with Initial Dose Rate of 40 r Per Hour

with time, and the lower broken line indicates the R_{eff} value. An inspection of these curves shows that a description of the events occurring within 48 hours will define most of the problem. By 48 hours almost 50% of the infinity dose has been received and the added daily increment following this is sufficiently small so that no change in lethality estimates need be made for short additional exposures. These statements are also true even if the calculations are based on the lower dashed line which takes into account the factor of biological recovery, using a 10% per day recovery rate. Thus, if there are methods available for protecting personnel during the early hours following arrival of fall-out, the greatest potential damage will be avoided.

In applying this type of analysis to idealized fall-out isodose contours, it is important to realize the significance of the figures used. These are figures applicable to a person standing unshielded in a level radiation field. It has been estimated[21] that the open field dose may be less by a factor of about 0.76 than the theoretically calculated dose for a smooth infinite plane surface, and that for designed shelters virtually complete protection could be provided.

In a situation where adequate shelter is available, control of dosage is possible by limiting the amount of time spent outside the shelter. With adequate early protection, fields which had very high initial dose rates may eventually be entered safely from shelters, with longer and longer exposures being possible as the field continues to decay. However, the field radiation levels at later times may still be high enough to constitute a hazard and the rate of fall-off may be sufficiently slow so that little time can be spent in the area without incurring risk. Existing conditions must be weighed in evaluating the potential hazard.

Application of Physical Contour Lines to Lethality Expectations.

In order to assess the significance of the physical fall-out measurements and contour line diagrams, these must be translated into

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21/ Hill, J.E., Effects of Environment in Reducing Dose Rates Produced by Radioactive Fall-out from Nuclear Explosions, The RAND Corp., R.M. - 1285-1, 1954.

biological terms. For the present, lethality is the parameter to be analyzed. The lethality expectation for an exposed population is dependent upon the time of arrival of fall-out, the dose rate at that time, the degree of shielding effective, and the time spent in the contaminated area. The analysis used here assumes instantaneous deposition of fall-out for any time of arrival and physical decay characterized by the $t^{-1.2}$ law. The biological factors of recovery and residual damage previously discussed are also included.

Figure 15 is a plot of 100%, 50%, 0% of lethality expressed in terms of the dose rate at time of fall-out. This figure was developed in the following manner. From Figure 13 the maximum ratio of $R_{eff}/r(t_0)$ for each (t_0) can be determined. This is shown in Table 5.

TABLE 5

t_0	Max. Ratio $R_{eff}/r(t_0)$
1	2.2
3	6.0
5	9.0
8	13.0
11	16.4
15	20.6
19	24.4

$R_{eff}/r(t_0)$ = Ratio of effective roentgens to the dose rate in r/hour at (t_0).

(t_0) = Time of arrival of fall-out, where total fall-out is assumed to occur instantaneously at any one location.

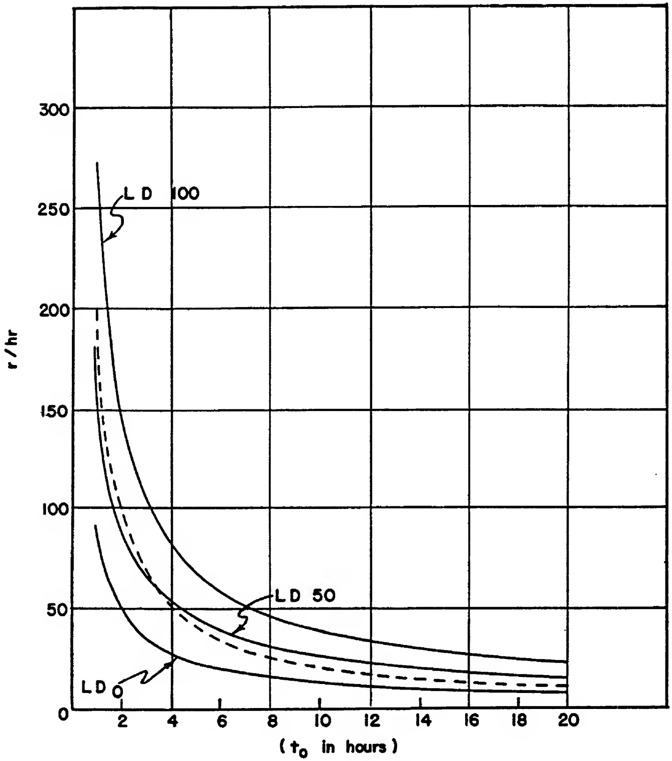
The maximum ratio is solved for $r(t_0)$ with:

$R_{eff} = 600\ r = LD_{100}$

$R_{eff} = 400\ r = LD_{50}$

$R_{eff} = 200\ r = LD_0$

The LD_0 curve for residual damage is calculated on the basis of a total cumulative dose to infinity of 1000 r. This leaves a residual of 200 r on the basis of a 20% residual damage fraction. The



(T_o = Time of Arrival of Fall Out

------ LD_o For Residual Damage Factor

Fig. 15. The Lethal Criteria Expressed in Terms of Dose Rate (r/hr) at (t_o)

calculation is based on the formula:

$$5 \times r \times t = 1000$$

where r is the dose rate in r/hr at time t, and t is the time of arrival of fall-out in hours. This curve is also plotted in Figure 15. It is worth noting that out to 20 hours it is still above the LD_0 curve for acute lethality. Figure 16 is an expression of the same data in terms of the H+1 hour dose rate. It is constructed by taking the respective dose rate measured at (t_0) and extrapolating back to H+1 hour according to the $t^{-1.2}$ decay law. These basic curves are used to develop Figure 17 which shows the extent of downwind lethal effects along the axis of the fall-out pattern for a 15 knot mean wind. This figure indicates the effect of increasing yield* on lethality expectation for these downwind locations under this specific wind condition.

By estimating the crosswind effect on the fall-out distribution, the data from Figure 17 has been extended to express lethality in terms of area as a function of fission yield and this is plotted in Figure 18. The reduction of lethal area accomplished by affording a protection factor of 5 is also plotted in Figure 18. As an illustration, assume that a 5 MT weapon is detonated on land surface. The unshielded LD_{100} and LD_0 contour lines enclose 2200 and 3600 square miles, respectively. If there is 80% effective shielding available, the LD_{100} area is reduced to 450 square miles and the LD_0 area to 1100 square miles.

The quantity of radiation accumulated from time of entry into an area to time of exit from the area is calculated by the formula

$$D = 5R_{H+1}(t_1^{-.2} - t_2^{-.2})$$

(1) D = total integrated dose of radiation in roentgens.

(2) R_{H+1} = Radiation dose rate at H+1 hour.

(3) t_1 = Time of entry in hours after detonation.

(4) t_2 = Time of exit in hours after detonation.

* For a thermonuclear weapon, the yield is assumed to be derived from

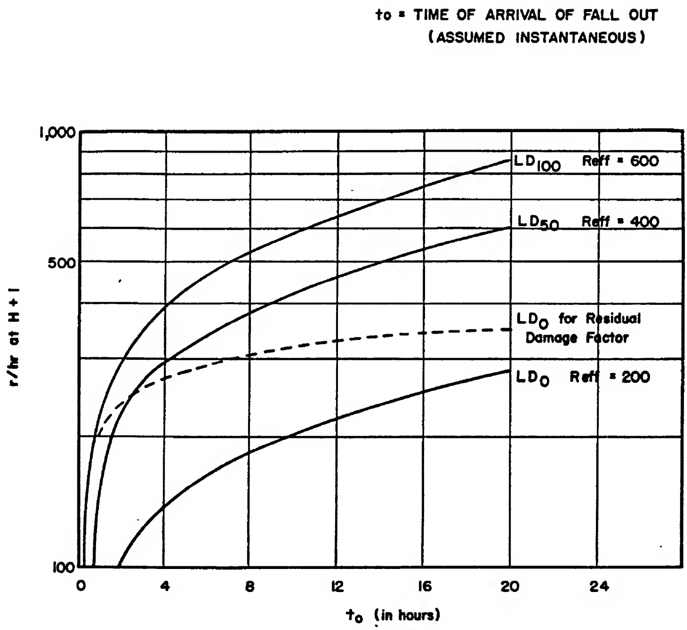


Fig. 16. Lethal Criteria Expressed in Terms of H+1 Hour Dose Rate for Various Times of Arrival of Fall-out or Entry into Contaminated Area Assuming Infinite Stay in Area

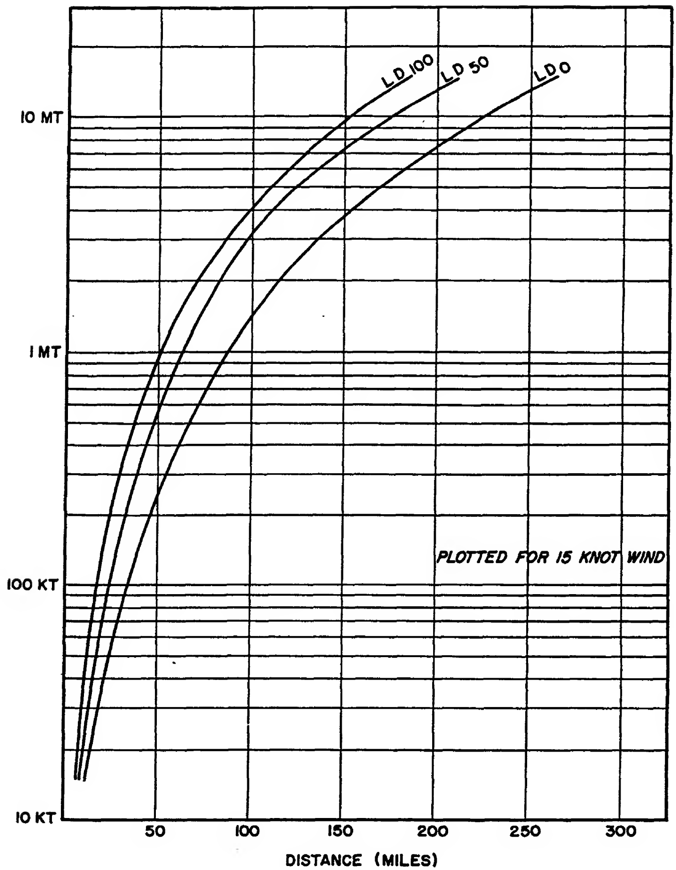


Fig. 17. Lethality Criteria Downwind (Along Contour Axis) As a Function of Yield

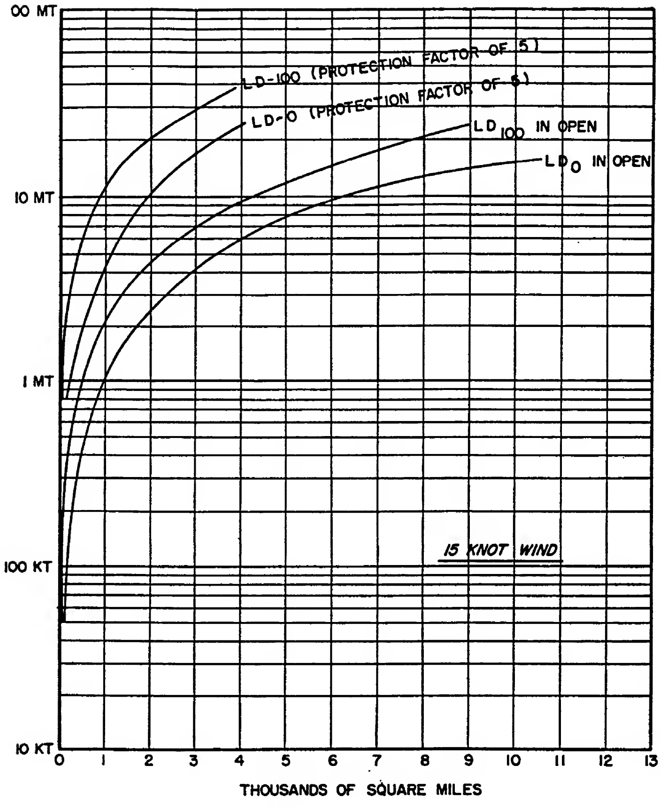


Fig. 18. Lethal Fall-out Areas

The relationships expressed in this equation were used to develop figures 19 and 20.

Figure 19 enables one to determine, from a knowledge of the H+1 hour dose rate, the total integrated dose received by an individual in 48 hours for any particular time of entry or any particular time of arrival of fall-out.

Figure 20 shows contour lines for radiation received up to H+48 hours, correcting for time of fall-out and assuming a 15 knot wind.

Radiation Injury Expectation. When exposed to sufficient radiation, personnel will show evidence of radiation injury varying from the acute radiation syndrome of nausea, vomiting, malaise, etc., to hemorrhagic phenomena and infection, with all the attendant clinical findings. Table 6 summarizes, essentially on the basis of the Hiroshima and Nagasaki experience, the effects of various instantaneous radiation doses.

TABLE 6

Summary of Effects Resulting from Whole Body Exposure to Radiation

Time After Exposure	Lethal Dose 600 r	Median Lethal Dose 400 r	Moderate Dose 300 to 100 r
First Week	Nausea and vomiting after 1-2 hours	Nausea and vomiting after 1-2 hours	Nausea
	No definite symptoms		
	Diarrhea Vomiting Inflammation of mouth and throat	No definite symptoms	
Second Week	Fever Rapid emaciation (Mortality probably 100%)	Beginning epilation	No definite symptoms
Third Week		Loss of appetite and general malaise. Fever. Severe inflammation of mouth and throat.	Epilation. Loss of appetite and general malaise.

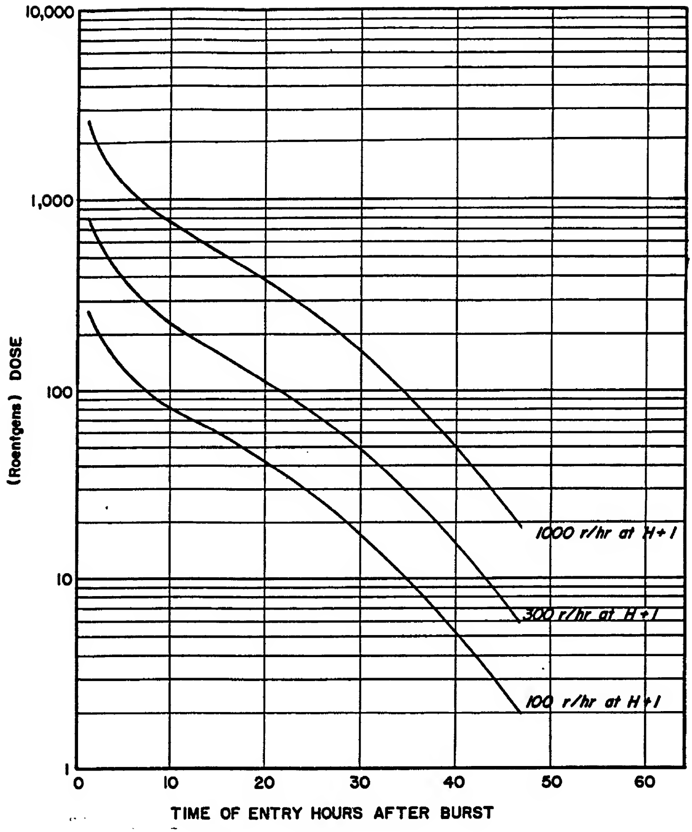


Fig. 19. Doses Accumulated up to 48 Hours After Burst Time for Various Times of Entry into Contaminated Area

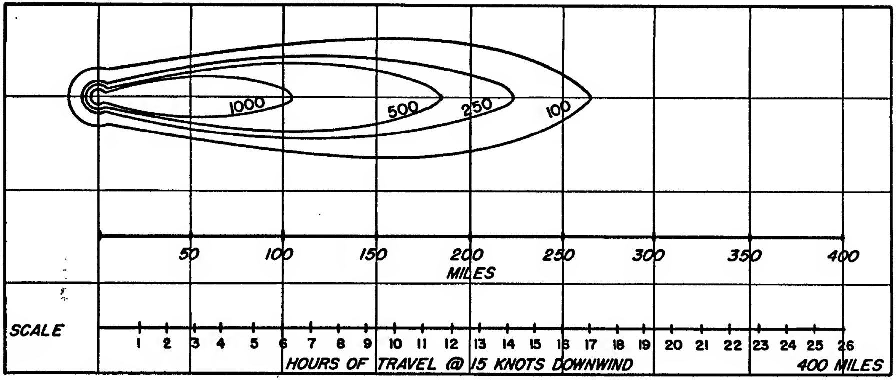


Fig. 20. Roentgens Accumulated from H+1 Hour to H+48 Hours for 15 MT Weapon

TABLE 6 (continued)

Summary of Effects Resulting from Whole Body Exposure to Radiation

Time After Exposure	Lethal Dose 600 r	Median Lethal Dose 400 r	Moderate Dose 300 to 100 r
Fourth Week		Pallor. Petechiae. Diarrhea and nosebleeds. Rapid emaciation. Death (Mortality probably 50%).	Sore throat. Pallor. Petechiae. Diarrhea. Moderate emaciation. (Recovery likely unless complicated by poor previous health or superimposed injuries or infections).

The injury expectation with non-instantaneous delivery of radiation cannot be schematically quantitated with the data available. As total dosage is protracted, there undoubtedly will be a decrease in the incidence of the acute toxic phase known as "radiation sickness". However, for radiation delivered over relatively short periods of time, such as one or two days, it probably is safe to assume that the hemorrhagic and systemic infection problems will remain almost the same as for instantaneous dosages. Various semi-quantitative statements are available, but these are based on opinion and no accurate data are available for critical study. The statements given by McLean in the Military Surgeon, which are substantially the same as those given by the Radiological Warfare Panel[22/] are summarized here. This is done to provide a "feel" for the problem.

22/ Noyes, W.A., et al., Radiological Warfare Report on Panel of Radiological Warfare, 1948, TID 204, SECRET, Restricted Data.

1. 10 r/day - Irregularly distributed over an eight hour day, probably would not render a unit ineffective if received daily for 30 days or more.
2. 25 r/week - Received within one day per week, probably would have no effect on combat ability for 8 weeks or more.
3. 50 r/day - Received for a week probably would not affect the efficiency of a fighting unit at once, but some individuals would be incapacitated by nausea and vomiting.
4. 100 r/day - Probably would be acceptable for not more than 1 or 2 days, after which incapacitation is to be expected.
5. 200 r/12 hrs - Can be regarded as equivalent to an instantaneous dose of 200 r.

The first item, 10 r/day for 30 days, represents a total of 300 r and an irreparable dose equivalent to about 60 r. Continuation beyond 30 days will be contingent upon assessment of damage ascribed to the total irreparable dose. The 25 r/week schedule for 8 weeks represents a total of 200 r and an irreparable dose of 40 r. The vagueness of the quantities cited is indicative of the real lack of data for setting standards.

In theory, it is possible to assume an infinite number of combinations of time-dose relationships. Accurate medical descriptions for all these conditions, however, are not possible. For an exposed population in a large fall-out area involving thousands of miles, the bulk of the exposures are likely to be supralethal or sublethal, and only a relatively small part of the area affected will be in the uncertainty range regarding lethal and injury effects.

On the basis of large animal studies conducted by Trum and

his associates[23/] it appears that completely effective functioning is not likely for persons who have received a dose in the lethal range. On this basis, the following generalization may be applied: within the first week, all personnel subject to radiation with an R_{eff} equal to or greater than the 5% lethal dose in 30 days are considered sick and should not be used for work of any kind.

Operation CASTLE Experience. The first shot of the CASTLE test series was fired 1 March 1954 on a reef at Bikini atoll, with a total energy yield of 15 MT,

Changing weather conditions around and after shot time resulted in deposition of a portion of the fall-out pattern from this shot over the populated atolls of Rongelap, Rongerik, and Uterik, although the heavier contaminated axis of the pattern lay north of these island groups. The populated islands of these atolls were evacuated promptly, but not before a group of natives on Rongelap had received an estimated whole-body dose of gamma radiation above 80 kev in the neighborhood of 175 roentgens. A small group of American service men on Rongerik received an estimated 95 roentgen whole-body dose, and a native group from Utirik about 15 roentgens before being evacuated. An island survey team monitored the islands of these atolls carefully over a period of several days beginning on the seventh day after the shot, making a valuable documentation of the fall-out intensities in the living areas involved, as well as on neighboring unpopulated islands.

As a result of careful observations made upon the exposed individuals and of analyses of the related physical data obtained from subsequent shots of the CASTLE series, a wealth of pertinent data on the radiation hazards of fall-out is now at hand. These data indicate that careful consideration must be given the external hazard problems associated with beta and gamma radiation from radioactive fall-out in

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23/ Trum, B.F., et al., Clinical Observations Upon the Response of the Burro to Large Doses of External Whole Body Gamma Radiation, Auburn Veterinarian, 8, 1952.

terms of the conditions likely to be encountered in the field as was the case for the accidental human exposures at CASTLE.

If in the case of the first CASTLE shot, the instrument readings in milliroentgens per hour at 7 to 9 days post-shot are extrapolated back to shot day and the value thus obtained integrated over the period of exposures using the $t^{-1.2}$ decay law, the values obtained compare favorably with dosages that would be estimated on the basis of the biological responses observed. The problem of measurement is not so simple and it seems possible that there may be factors omitted from the oversimplified estimation procedure just cited that would tend to lower the values obtained. Among these are:

(1) The travel time of fall-out, which may vary from estimates made.

(2) The gradual build-up of fall-out, which makes determination of a single "arrival time" uncertain.

(3) The shielding effect of special environmental conditions, such as buildings, trees, and clothing.

These might be counteracted by other factors not directly considered which would tend to raise such a value:

(1) The geometry of exposure.

(2) The adhering of particles to clothing and skin.

(3) Increased intensities below the 3 foot measuring level.

(4) The biological recovery factor in prolonged exposure times.

Thus a cancellation of errors may permit by a fortunate coincidence the use of a simple straightforward calculation to obtain a quite valid estimate of the dose involved.

The temporary epilation in the Marshallese suggests the dose to exposed skin on Rongelap was approximately 10,000 rep of beta radiation. Because of evidence of completely intact skin under clothing, the dose to the protected skin was probably less than 5000 rep. Thus the CASTLE data suggest that the clothing worn by exposed persons pro-

vided at least as much protection as implied by the broad estimate for Army field clothing to the effect that "... the average field issue clothing will stop approximately one-half of the incident beta radiation from fall-out material".

It has long been a moot question whether within an intense fall-out field the beta burn problem could be the factor limiting the period of exposure of personnel. CASTLE provided an unexcelled opportunity to observe such a situation. Personnel receiving whole body gamma doses of about 200 roentgens suffered no burns under the clothing except where the radioactive material was carried by perspiration or body motion under a collar or cuff. Over unclothed areas of skin, however, burns were sufficiently severe to reduce the efficiency of personnel more than would be predicted from the exposure to the concomitant gamma component. Thus, from CASTLE data has come the fairly defensible statement that for well clothed personnel in a fall-out field, gamma measurements alone will suffice to determine the radiological effects to be expected and the permissible time of entry into, or period of exposure within, such an area.

<u>The Beta Hazard</u>. The term "beta burn" as used here is damage to the skin by ionizing radiation. The radiations primarily effective for this phenomenon are beta particles and low energy gamma rays. Thus, the term "beta burn", as generally used is a misnomer to the extent of the contribution by the low energy gamma or x-rays.

Skin burns occur when the quantity of radiation absorbed by the living layers of skin exceeds a certain critical level. The flux of radiation necessary to cause a given degree of skin damage depends upon the energy and kind of radiation arriving in the critical area. The thickness of the outer protective layer of dead tissues, plus the attenuating effect of clothing, determines the radiation dose delivered to the living tissues.

The energy of gamma radiation is frequently referred to in terms of half-value thicknesses while that of the beta radiation is in

terms of E_{max}. These are difficult terms to use when assessing the degree of damage caused by a spectral mixture of beta particles and gamma rays. It is more convenient and useful to talk in terms of the per cent of total beta and gamma radiation that is absorbed in the critical layers of skin.

The outer layer of protective dead skin cells varies in thickness from 0.1 mm, weighing 10 mg/cm^2, over the anterior aspect of the arm to a thickness many times this value over the sole of the foot and the palmar surface of the hand. The minimum beta energy necessary to penetrate a thickness greater than 10 mg/cm^2 is 80 kev. Thus, 80 kev is the minimum beta energy to produce skin damage. It has been calculated that somewhat more than 50% of the beta rays emitted during the first few weeks after fall-out has occurred have less than this cut-off value and thus would be absorbed in the protective cornified layer and produce no biological effect.[24/] The somewhat less than 50% of the beta particles remaining has an average energy of about 600 kev and can penetrate well into the body with a large portion being absorbed by the critical living layers of skin, and this constitutes the hazardous fraction of the beta spectrum.

The effective energy for gamma radiation to produce skin burns lies between 1 and 100 kev. It is estimated that about 10% of the total gamma radiation from fall-out is within this range.

The quantity of beta radiation required to cause injury to the skin, or beta burns, has been found in the laboratory by using pure beta emitters with beta energies known to be about 500 to 700 kev.[25/] The investigators found that 2000 roentgen equivalent physical (rep) is the minimum beta dose which will cause visible reddening of the skin.

24/ Cronkite, E.P., et al., Study of the Response of Human Beings Accidentally Exposed to Significant Fall-out Radiation, Final Report Project CASTLE 4.1, WT-923, October 1954, CONFIDENTIAL.

25/ Personal Communication, Health Physics Division, Hanford Operations, February 1955.

8000 rep will cause blistering of the skin and temporary loss of hair. Healing of ionizing radiation burns will be somewhat slower than from thermal burns, but will probably be complete with no undue increase in numbers of secondary infections. 12,000 to 14,000 rep will cause deep blistering followed by permanent scarring. Until further work is reported, it appears that a value of 2000 rep should be considered the threshold dose for skin burns; however, on the skin of the hands, where there is increased thickness of palmar cornified tissue, protection against up to 3000 to 5000 rep air dose would be provided by the cornified layer as quoted by NavMed P-1330.

The biological effect of beta radiation delivered to the whole body may be considered to vary directly with the dose rate within limits defined by a recovery rate and a non-recoverable fraction of the total dose. Estimates of the mid-lethal dose of whole body beta radiation are widely variant and cannot be entirely resolved. For example, it has been found by Zirkle, et al.,[26] that in comparing the LD_{50} of baby rats, mice, grown rats, guinea pigs, and rabbits, the log of the gram rep absorbed, i.e., the total energy absorbed by the animal, varies directly and linearly with the logarithm of the weight of the animal. This suggests that body volume as well as surface area involved are determining factors in the degree of mortality produced. If a toxic substance liberated by damaged tissue cells plays a role in lethality, it would be consistent with the observed data in that, as the body volume to skin surface ratio increased, the toxic material per unit body volume would decrease. Thus, if this experimentally determined relationship of body size is extrapolated to man, a dose of the order of 40,000 beta rep is obtained as LD_{50} for man. On the other hand, a fairly sound assumption can be made that a dose causing a moderate degree of local skin damage, if applied to the entire body, will result in death in at least a moderate percentage of those involved. This

26/ Zirkle, R.E., Biological Effects of External Beta Radiation, National Nuclear Energy Series, Div. IV, Vol., XXII, E., 1951.

appears to be a valid assumption in the case of thermal burns, and, if true, indicates an LD_{50} for man in the range of 5000 beta rep whole body exposure.[27/] However, from a practical point of view, considering a fall-out radiation field, these values are probably academic in nature. The ratio of measurable gamma radiation in air to beta radiation, plus unmeasured low energy gamma radiation on the skin, under clothing indicates that the gamma radiation dose is the limiting exposure.[28/] The short range of beta particles practically necessitates actual deposition of fall-out particles upon the skin in order for skin burns to occur.

The measurement of the effective beta plus low energy gamma radiation to the simultaneously measured gamma radiation may be referred to as the beta/gamma ratio. This beta/gamma ratio has been studied by many investigators. The values obtained vary from 3/1 to 140/1. These differences are primarily due to the methods, instrumentation, and detector geometry used.

When comparing dosage of beta and low energy gamma radiation received by the ankle, protected by a layer of clothing, to a film badge worn on the shoulder, a ratio of 2.5/1 has been obtained. Other investigators using laboratory techniques and making direct surface measurements of beta to gamma intensities have arrived at a value of 140/1 or even higher.[29/] Since the range in air of fall-out beta particles is about six feet, the ratio of intensities will increase as measurements of radiation dose are made closer to the source.

It is possible to equate the observed degree of skin damage suffered by the Marshallese natives during Operation CASTLE to known

27/ Broido and Teresi, Tolerance in Man to External Beta Radiation, Technical Manual No. 4, USNRDL, August 1954.

28/ Brennan, J.T., Beta-Gamma Skin Hazard in the Post-shot Contaminated Area, UPSHOT-KNOTHOLE Proj. 4.7, December 1953, CONFIDENTIAL.

29/ Condit, R.I., Dyson, J.P., and Lamb, W.A., An Estimation of the Relative Hazard of Beta and Gamma Radiation from Fission Products, USNRDL, AD-95H, April 1949.

dose-effect data. It would appear that the skin burns and temporary epilation which occurred indicate a surface dose from fall-out particles deposited on the skin to be equivalent to a dose in the order of 10,000 rep of 0.5 - 0.7 mev beta. The ratio of the intensity of beta plus low energy gamma radiation at the surface of the skin, to the high energy (above 80 kev), gamma component measured 3 feet above the ground, in this situation approximates an effective beta/gamma ratio of about 50/1. It is felt that in spite of the wide range covered, the foregoing beta/gamma estimates, extending from 2.5/1 to 140/1, are still reasonably compatible when it is considered what each describes and how the measurements were made. Thus, it should be possible to determine by comparison with known data a single procedure for calculating a useful ratio of the unmeasurable beta plus low energy gamma skin hazard to measurable gamma radiation in a fall-out field. The Marshallese incident has pointed up the fact that beta burns will occur at sub-lethal gamma levels only when particles come into contact with bare skin. According to laboratory hematological data on these natives, the whole body gamma dose approached lethal levels, yet these natives who, for the most part, remained in the open during active fall-out, received burns limited to unclothed parts of the body or in areas where perspiration carried contamination into clothed areas.

Beta radiation is known to have a carcinogenic effect* on the skin. Among the few relatively undisputed statements in this regard is the observation that before a skin cancer has been observed in man, evidence of radiation injury has been apparent. This suggests that the dose required to produce skin cancer is at least as high as the dose required to cause observable skin damage. Whether this observation taken from chronic exposure cases holds true for acute exposures is not known. It would seem likely that because of the injury recovery factor a much higher total dose must have been received in the chronic

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* Carcinogenesis (the action of an agent upon a tissue producing cancer, i.e. radiation)

cases to produce evidence of injury; hence, a higher threshold for cancer production than that for minimal damage from an acute dose. Skin cancer production shows little radiation time-intensity dependence and, like the genetic effect to be discussed later, the incidence is probably a linear function of total dose.

The measures which may be taken to prevent beta burns of sufficient severity to reduce the efficiency of military or civilian populations are quite simple and effective. The cornified layer of skin covered with loose fitting clothing provides the minimum protection necessary to prevent serious injury to the living layers of the skin. Brennan and his co-workers have reported the following thicknesses for standard items of Army apparel:

Item	Mgm/cm^2	
Undershirt	17	0.1 Mev → E_{max}
Shorts	12	"
Shirt	29	
Trousers	77	
Field Jacket	186	0.6 Mev

From beta range considerations, it can be shown that the above items of clothing can effectively protect against beta energies from 0.1 mev to 0.6 mev. The protection afforded by ordinary clothing is easily augmented by wearing gloves and by frequent washing with soap and water when working in an area of fall-out or suspected contamination.

<u>The Genetic Problem</u>. In considering the genetic problem due to local fall-out, the probability must be considered that "local" may involve an entire nation such as the United States in the event of an atomic war. For surface bursts, approximately 50% of the fall-out radiation has been accounted for locally. The radiation risk at early times after fall-out has begun is greater than at later times due to the decay characteristics of fission products. These two facts indicate that potentially at least the genetic problem due to total fall-out may be primarily determined by the effects brought about in

the local fall-out area and that the added hazard due to world-wide distribution of fission products may be of secondary importance.

The fundamental facts of radiation genetics as presented by such leading geneticists as H. J. Muller, A. H. Sturtevant, C. Stern, and others, have been generally accepted.[30,31,32,33,34/] These are:

1. Radiation to the gonads will produce mutations in germinal cells.

2. The mutation rate is proportional to the total dose of radiation received and is independent of dose rate.

3. There is no threshold for mutation effect.

4. Mutations are primarily deleterious, and may be classified as follows:

   a. Lethals - dominant.

   b. Lethals - recessive: complete and incomplete.

   c. Deleterious - non-lethal but causing some percentage decrease in efficiency.

5. Mutations produced by artificial radiation are the same as those already produced and being produced spontaneously.

6. Genetic death is the removal of a fertilized egg cell, or the individual developing therefrom, before it has a chance to reproduce.

Quantitative genetic concepts are derived from experimental

30/ Stern, C., Principles of Human Genetics, W.H. Freeman Co., 1950.

31/ Muller, H.J., Radiation Damage to Genetic Material, American Scientist, 38, 1950.

32/ Sturtevant, A.H., The Genetic Effects of High Energy Irradiation of Human Populations, Engineering and Science Monthly of California Institute of Technology, January, 1955.

33/ Plough, H.H., Radiation Tolerance and Genetic Effects. Nucleonics 10, 1952.

34/ Muller, H.J., The Manner of Dependence of "The Permissible Dose" of Radiation on the Amount of Genetic Damage, Acta Radiologica 41:5, 1954.

work performed on the fruit fly, drosophila. These data are extrapolated to the human situation assuming an increased sensitivity factor of 10, based on mammalian genetic studies with mice. Whereas qualitatively man should react in a manner consistent with the fundamental genetic facts as determined by lower forms, the quantitative extrapolation carries more uncertainty. Some of the quantitative concepts so developed are:

1. 1 r = 1 lethal mutation in 1000 germ cells or 1 lethal mutation in 500 conceptions.

2. Detrimental mutations are roughly twice as frequent as lethal mutations.

3. Approximately 4% of recessive lethals will find expression as a genetic death in each generation.

4. The irradiation mutation rate of mature germ cells appears to be about twice the rate of immature germ cells.

5. Detrimental mutations will account eventually for one genetic death per mutation.

6. From statistical considerations it has been estimated that one genetic death will cause elimination of at least two to three mutations.

In order to obtain some idea of the genetic effect of fall-out radiation on a population, consider the following situation.

<u>Assume</u>:

1. Total population of 100 million people.

2. Population is stable and requires 2,700,000 births per year. For a procreative period of 25 years, this requires 67.5 million births per generation.

3. A dose of 100 roentgen is delivered to the gonads of each member of the population due to fall-out radiation.

If 1 r = 1 lethal mutation in 1000 germ cells or 500 conceptions, for 100 r there will be one lethal mutation in 5 conceptions. Since the generation exposed will produce 67.5 million births, there will be

about 13 million mutation-bearing conceptions of the lethal variety. A small but undetermined proportion of these will be expressed as lethal dominants and will be eliminated in the first generation, many as early miscarriages. Approximately 4% of the recessive lethal genes will also come to expression as genetic deaths in the first generation and these will amount to approximately 20,000 conceptions per year out of the expected 2,700,000 births per year. If we add to this the expected genetic deaths from the detrimental mutations, twice the number of lethals with an assumed maximum of 4% for the detrimental factor, there can be a total of 60,000 genetic deaths per year for the first generation out of the expected 2,700,000 births per year. This rate will decrease with time until the total number of genetic deaths equals approximately one-half to one-third of the 13 million lethal plus 26 million (detrimental) mutations.

It is worth pointing out that an informal exercise at RAND which assumed 150 15 MT weapons dropped over the United States, east of the Mississippi, resulted in the delivery of approximately 86 r/person to the total population of that area, i.e., east of the Mississippi, on the further assumption that shelter giving 90% protection was available and used by everyone. This condition would reduce the totals given in the example above by a factor of 2, because of the fact that the immature germ cell mutation rate would apply for the bulk of the radiation exposure. The amount of additional genetic damage caused by radiation after people leave their shelters will depend on decontamination, weathering, gross terrain shielding, and other factors.

It appears, therefore, that a large amount of radiation will not present an inordinate genetic effect as long as the radiation is applied to one generation only and is not repeated. Repeating the dose discussed above, generation after generation, would before many generations reach a new mutation rate which could be incompatible with species survival.

Consider now the question of residual low level radiation from one war acting on succeeding generations, causing a new equilibrium for mutation rate. On the basis of residual activity present, according to the Hunter-Ballou tables, the only significant background gamma radiation after 20 years will be contributed by the element cesium-137, with a 37 year half-life, which decays to barium-137, with a 2.5 minute half-life, which emits a 0.7 mev gamma ray. Only gamma radiation is considered since practically no beta radiation will reach the germinal cells.

It is of interest to calculate the amount of fission yield which would have to be released in order to double the natural background radiation dose-rate due to the uniform distribution of artificial radioactive materials at some future time, e.g., 20 years. Assume:

1. Background radiation = 0.0125×10^{-3} r/hr = 0.3 mr/24 hours.

2. Cesium-137 is the long-lived isotope with a strong gamma which will be the main contributor to increasing the background. 70 curies of cesium-137 are formed per KT fission yield.

3. Area of earth = 2×10^{8} square miles.

4. One megacurie of cesium-137 per square mile will give a radiation dose of 4 r/hr at three feet above ground.

5. Uniform world-wide distribution of the isotope.

Thus:

a. $$\frac{\text{70 curies of cesium-137}}{2 \times 10^{8}\ \text{square miles}} = 3.5 \times 10^{-7}\ \text{curies cesium-137/mi}^2\text{/KT}$$

b. $I_t = I_o e^{-\lambda t}$. This is the equation for radioactive decay for a single isotope in which

$I_t = 0.0125 \times 10^{-3}$ r/hr

I_o = radiation dose rate due to cesium-137 at H+1 hour

$e^{-\lambda t} = 0.69$ for t = 20 years.

$$I_o = \frac{I_t}{e^{-\lambda t}}$$

$$= \frac{0.0125\times10^{-3}}{0.69} \text{ r/hr (natural background)}$$

$= 0.0181\times10^{-3}$ r/hr, the dose rate of cesium-137 required at H+1 hour to give the desired dose rate at 20 years.

c. Then, to obtain the curies of cesium-137 per square mile needed to give 0.0125×10^{-3} r/hr at 20 years,

$$\frac{1 \text{ megacurie/mi}^2}{4 \text{ r/hr}} = \frac{x}{0.0181\times10^{-3} \text{ r/hr}}$$

$x = 4.5$ curies cesium-137/mi^2 at H+1 hour to double the background at 20 years.

d. Then the fission yield required would be,

$$\frac{4.5 \text{ curies/mi}^2}{3.5\times10^{-7} \text{ KT/curie cesium-137}} = 1.1\times10^7 \text{ KT} = 1.1\times10^4 \text{ MT.}$$

The result indicates that 1.1×10^7 KT or 1.1×10^4 MT must be produced in order to double the background by gamma radiation at 20 years. Because the spontaneous mutation rate is only partly due to background radiation, the numerical estimate of 1.1×10^4 MT given above probably represents a lower limit to the value of fission yield required to double the spontaneous mutation rate. A non-uniform world-wide distribution would alter this figure in direct proportion to the non-uniformity of the distribution in the major area under consideration.

Finally, mention should be made of the spontaneous abortion rate. According to one authority, "a conservative estimate would indicate that about every fifth pregnancy in private practice ends in spontaneous abortion, and the percentage would increase considerably were the very early cases taken into account."[35/] Since abortions are genetic deaths, it can be seen that the population of 100,000,000 discussed above, with its 2,700,000 births per year would have in excess of 500,000 abortions annually to be counted as genetic deaths independent of any artificial radiation experience. It is also worth

35/ Stander, H.J., Williams Obstetrics, 8th Edition, Appleton-Century Co.

noting that many of these early terminations of fertilized egg cells may represent a natural mechanism for removal of many abnormal conceptions. Although purely speculative, this concept does support the possibility that a large proportion of the artificially mutated genes would be eliminated by nature before becoming a significant social burden.

B. Evaluation of the Human Hazard Due to Radioactive Fall-out: Internal.

The external hazard due to fall-out radiation is essentially confined to the local fall-out area. The internal hazard, i.e., the hazard created by internal deposition of various isotopes in humans, exists both in the local fall-out area and world-wide. Quantitative aspects of fall-out and fractionation of critical elements suggest that the hazards to be expected locally are very great compared to the world-wide problem. If it is assumed that local fall-out areas will be large because of large numbers of bombs being dropped, then the local area hazard is likely to be the critical consideration for internal as well as external radiation injury.

Criteria for Assessment of Biological Significance. All of the radioactive components of fall-out material are hazardous to some extent. It is not necessary, however, to evaluate in detail the radiation injury due to each of these components. In a general assessment of internal hazard it is sufficient to find the component or components which are responsible for the major part of the hazard. From the point of view of safety, the most critical element becomes the limiting factor and any standards set for the critical element automatically remove the others from need for consideration.

In estimating effects above the safety level, it becomes necessary to add all elements which are of appreciable significance in their contribution to the total effect. As will be shown below, Strontium-90 appears to be not only the critical element for determining safety standards, but it is also responsible for practically all of the long-term effect, and therefore the parameters relating to this

element define practically the whole problem of long range internal hazard.

The analysis leading to the identification of strontium-90 as the only element requiring consideration is not sufficiently definitive to close the subject. A case in point was the unexpected finding of iodine-131 in seemingly appreciable amounts in individuals following the CASTLE series of detonations in the Pacific in the spring of 1954. The dosage delivered to individuals from this experience could not be calculated precisely because of the sparsity of the data, and further work will be needed to determine the hazard due to I^{131}.

The relative importance of strontium-90 to strontium-89 is another case in point. The seriousness of the strontium-90 problem is predicated on the hypothesis that this isotope will work its way into the biosphere over a considerable period of time. Should this hypothesis require modification, then strontium-89 may increase in relative importance. This question will be analyzed in detail in a later section dealing with the strontium-90 problem.

In order to assess the biological significance of radioactive fall-out as an internal hazard, it is important to identify the pathological process which will be the limiting parameter. Among the pathological processes to be considered are the effects on the bone marrow leading to anemia, direct tissue destruction of gastro-intestinal and urinary structures, genetic effects, and carcinogenesis. Because of the low levels of radiation which have been known to cause carcinogenesis it seems likely that this may be the critical process. Since there is an inverse relationship between the time and the amount of material needed for the effects due to internal deposition, the search immediately centers on the long-lived isotopes which will remain fixed in the body for long periods of time.

The 1949 Project GABRIEL report[36/] contains the only fairly

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36/ Smith, N.M., Project GABRIEL Report, Los Alamos Scientific Laboratory, November, 1949, SECRET Restricted Data.

systematic treatment of the relative internal hazards of the elements found in radioactive fall-out material. Consideration of the problem has led to the conclusion that the bone seeking elements are the ones most likely to be the major cause of hazard for long-term internal effects. The comparison of the various elements produced included the following parameters in calculating relative effect.

1. Fission yield
2. Natural decay constant (λ, in Table 7)
3. Biological elimination constant (λ_b, in Table 7)
4. Oral absorption, %
5. Deposition fraction in bone
6. Average energy of emitted particles and relative biological effectiveness.

For comparative purposes, Table 7 has been compiled on the basis of metabolic data taken primarily from the work of J. G. Hamilton[37/] to show the approximate relative internal hazards posed by various radioisotopes found in bomb debris.

This table indicates that within a short time after detonation strontium-89, strontium-90, and barium-140 are relatively comparable in their effects. As time passes, however, strontium-90 becomes increasingly important and by the end of the first year it is the most important element to consider in hazard evaluations.

Maximum Permissible Concentrations of Radioisotopes. Radioactive isotopes are damaging agents to humans, apparently without threshold effect, when one considers genetic damage and possibly without threshold for carcinogenesis except for the fact that low doses may have a latent period greater than the human life span. In a true biological sense, therefore, limits of acceptable damage must be set and the amounts of material which will not exceed these limits determined.

37/ Hamilton, J.G., The Metabolic Properties of the Fission Products and the Actinide Elements, Rev. Modern Physics 20:718, 1948.

TABLE 7

Element	Radi-ation	Energy (mev)	$\lambda(yr^{-1})$	$\lambda_b(yr^{-1})$	Approximate Relative Hazard At *t = 0	*t = 1 yr
Sr^{89}	β-	1.5	4.75	1.0	38	.038
$Sr^{90}+Y^{90}$	β-	0.6+2.5	00.0276	1.0	20	20.
Ba^{140}	β-	1.05	19.7	7.0	30	3×10^{-11}
Y^{91}	β-	1.7	4.43	0.5	0.127	2.1×10^{-4}
Ce^{144}	β-	0.3	0.93	2.0	0.021	5.4×10^{-3}
Pr^{143}	β-	1.0	18.1	2.0	0.25	10^{-12}
Gl^{147}	β-	0.2	0.186	2.0	0.0037	2.8×10^{-3}
$Zr^{95}+Cb^{95}$	β-	0.4+0.15	2.4	8.3	0.0044	1.3×10^{-5}
Pu^{239}	α^{++}	4.0	3.13×10^{-5}	0.3	0.021	2.1×10^{-2}

* t = 0 implies that the products are ingested immediately on detonation of bomb;

t = 1 yr means that an average of 1 year elapses before the first products are ingested.

The primary source of codified information on this subject comes from the published report of the Subcommittee on Permissible Internal Dose of the National Committee on Radiation Protection[38/]. The standard used was to limit the radiation dose to the most critical tissue to 0.3 r per week. For any particular isotope the tissue with the greatest concentration was used and various metabolic data relative to per cent of absorption, rate of turnover and excretion, etc., were taken into account.

A departure from this general principle was adopted for those isotopes which localize in the skeleton. The distribution of skeletally deposited isotopes cannot be considered uniform so that the

38/ National Bureau of Standards Handbook 52, March, 1953.

concentration and therefore the dose of radiation cannot be accurately calculated. The method of approach adopted was to compare in animals the toxic effect of a particular isotope to that of radium and to use these data for establishing the permissible dose in man equivalent to the 0.1 microgram of radium which is the accepted maximum permissible dose.

Radium deposition in humans has occurred in hazardous amounts and several studies have been made to estimate the lowest levels which will cause damage. The Bureau of Standards in 1941 set 0.1 microgram as the maximum permissible level of body burden for radium. This was based on a series of cases where death had occurred with a level of radium as low as 1.2 micrograms. Since the maximum permissible level embodies a safety factor of about 10, the level of 0.1 microgram was established.

The radium preparations to which the above cases were exposed also contained other radioactive materials, principally mesothorium. Since the mesothorium component was not estimated, it was felt that the damage attributed to the calculated radium levels must be due in part to the mesothorium and therefore the radium standard would have been set too low.

In order to investigate this problem, W. B. Looney[39] has compared the cases involved in the mesothorium-radium series with a series of patients given radium preparations as a form of medication. His studies suggest that in the two series of cases there is a threshold level for detectable disease at about 0.5 - 1.0 microgram of radium firmly deposited in the skeleton. Within the limits of accuracy of measuring the response to various levels of radium no increased effect could be noted due to the mesothorium content of the patients exposed to the mixture. From the viewpoint originally set for the concept of "Maximum Permissible Levels", Looney's study indicates that the value

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39/ Looney, W.B., U.S. Naval Hospital, National Naval Medical Center, Bethesda, Maryland, 1955, Personal Communication.

for radium might have to be lowered by a factor of 2. Nevertheless, for purposes of calculation, the tolerance level of 0.1 microgram of radium as the maximum permissible concentration still stands as the commonly accepted value.

The Radio-strontium Problem. Strontium-90 is produced in considerable quantity in nuclear detonations, the currently accepted value being approximately 1 gram of strontium-90 per KT of fission yield. Theoretical analysis and actual experimental findings discussed earlier suggest that strontium-90 is produced in a manner which makes it easily available for incorporation into the biosphere. Adding these characteristics of relatively large scale production and physico-chemical availability to the previously indicated properties of the physical half-life, relatively high bodily ingestion and absorption, and its bone seeking properties which give it a long biological half-life, it is evident that the importance of this element is quite well established with regard to internal hazard. For large populations the greatest hazard will be to those who have to bear the burden of isotopes for the longest period of time, i.e., the fetus and child. In addition, the sensitivity of young, rapidly growing tissue to radiation damage is greater than that of mature, more slowly growing tissue, and this adds to the risk of the younger age groups.

Strontium-90 has never been administered to human beings in dangerous amounts so far as is known at present. The work done on this problem has attempted to correlate strontium-radium effects in animals and to apply this relationship to the maximum permissible concentration of 0.1 microgram of radium in humans, thereby establishing the maximum permissible concentration for strontium-90. Brues' experiments with strontium-89 are the only ones applicable to the problem of establishing the maximum permissible concentration for strontium-90 in humans. On the basis of Brues' work with strontium-89 in mice, and mouse radium data, a strontium-89 to radium toxicity ratio of 1:10 on a microcurie basis was established. It has been stated that the

radiation from radium dose in humans, per microcurie, is twice that in mice due to exhalation of less radon and that therefore the strontium-89 to radium ratio in humans should be 1:20. Since strontium-90 has two disintegrations in its decay chain to one for strontium-89, this ratio is set at 1:10 for the strontium-90 to radium in humans. The maximum permissible concentration of radium on a microcurie basis is 0.1 microcurie; therefore, the maximum permissible concentration for strontium-90 has been set at 1.0 microcurie.

Since strontium-89 might be expected to follow the same pathway through the biosphere as strontium-90, it is instructive to examine the possibility that the former isotope may be an important factor in the over-all strontium problem.

Fall-out studies to date tend to indicate that a short-cut may exist in the soil to plant to animal cycle; further, that some if not most of the animal ingested strontium comes from the mechanical deposition of fall-out upon the exposed surfaces of the leaves of plants rather than through a complex soil to plant nutrient cycle. This, coupled with the fact that cows' milk, the main source of radio active strontium, is consumed in a matter of several days, can appreciably shorten the previously estimated length of time between fission product formation and human bone deposition. It is possible, allowing one week for fall-out to occur, a second week for strontium to be ingested by a dairy cow, and a third week to be ingested by man, that deposition in bone could begin to occur in detectable amounts within a period of several weeks after a bomb detonation.

A consideration of these two isotopes of strontium in terms of various controlling factors may be summarized briefly as follows:

1. Strontium-89 and strontium-90 are produced in amounts of approximately 1 gram each per kiloton fission yield.

2. These radioisotopes are biologically available and can follow the pathway of calcium both in the plant through animal to man cycle and in metabolic deposition in bone.

3. The excretion rate is quite important. A single dose ingested will be 50% excreted in approximately two weeks and 95% excreted within a year. The variously estimated 2-5% remaining may be considered permanently fixed in the bone.

4. Strontium-90 has a half-life of 19.9 ~~20 to 30~~ years and decays through the radioactive isotope yttrium-90 to the stable element zirconium-90 by two beta emissions (.7, 2.2 Mev). Strontium-89 has a half-life of 55 days and decays by a single beta emission (1.5 Mev) to stable yttrium-89.

A graphical comparison in Figure 21 shows that the strontium-89/strontium-90 ratio of initial intensities is approximately 130/1. If this is reduced by a factor of 2 to take into account the two to 1 ratio of beta particles emitted per disintegration by strontium-90, it results in a 65/1 initial radiation intensity ratio. This ratio by virtue of the relatively long half-life of strontium-90, may be considered as being reduced by a factor of 2 every 55 days. The curves in Figure 21 indicate the relative intensities of strontium-89 and strontium-90 present at times after deposition in bone assuming the limiting extreme of immediate deposition after detonation. With proper graphical presentation, the areas under the curves give the relative proportions of strontium-89 and strontium-90 radiations that will occur in the bone. Calculations based upon the above considerations indicate that strontium-90 will be the greater contributor of the total dose to bone.

Pathway Through the Biosphere. Some qualitative and quantitative understanding of the behavior of strontium-90 as it passes through the physical environment is necessary in order to interpret the data relating to pathway through the biosphere. No significant studies have appeared which suggest that inhalation as a pathway into the human is important. Therefore, the mechanical and biological transport of strontium-90 through the food chain will be given primary consideration. Intake of water contaminated with strontium-90 will be considered as augmenting the food chain.

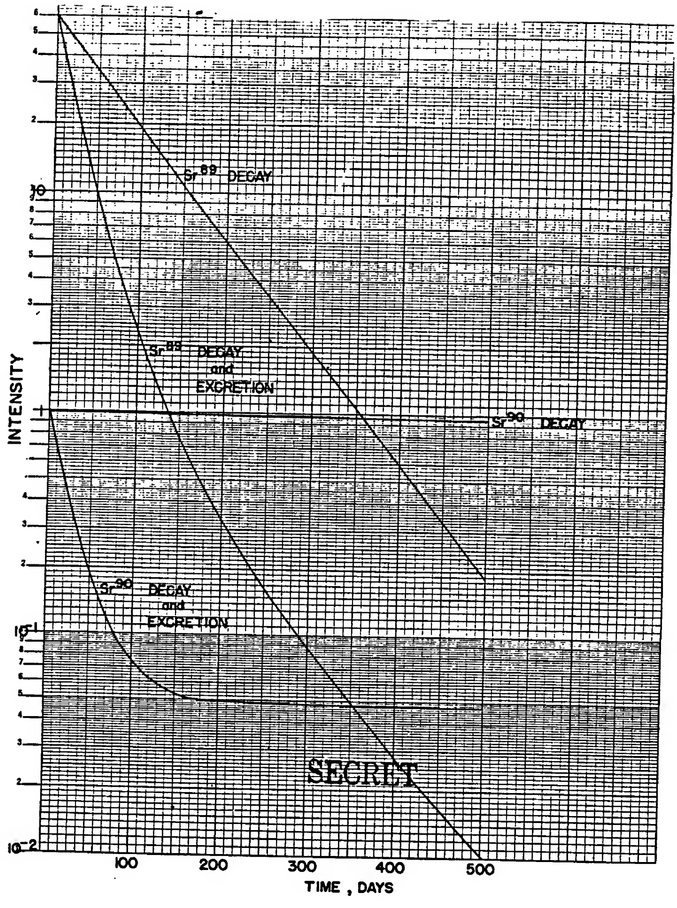

Fig. 21. Cumulative Loss of Sr^{89} and Sr^{90} By Decay and Excretion

One important link in the strontium-90 food chain is the pathway through plants. The significance of the amount of strontium-90 uptake by plants relates to its transport and final deposition in the bones of humans. There are many complicated mechanisms concerned in the soil-plant relationship which are still to be evaluated. These, when they are worked out, will make possible the determination of the ultimate significance of a particular level of soil contamination at a particular time.

The strontium/calcium ratio for plant root uptake in nutrient solutions is 1.0. The U.S. Department of Agriculture studies[40/], however, indicate that in American soils the average uptake departs from this experimental value. Menzel has calculated a factor of $k_{Sr} = 0.36$ on the basis of

$$k_{Sr} = \frac{(Sr/Ca)\ \text{plant}}{(Sr/Ca)\ \text{soil}}$$

The available calcium in the soil determines the amount of strontium-90 taken up by the plant. Menzel has shown that over a range of 0.7 to 48 milli-equivalents of calcium per 100 gms of soil, the strontium-90 uptake was inversely proportional to the amount of calcium present.

Some experiments have been conducted which relate uptake of strontium-90 by plants to soil depth distribution of this contaminant. Here root depth is the critical parameter. The over-all significance of this principle will depend upon calculations relating actual depth of contamination to root depths for various food crops. The total problem, however, has not yet reached a degree of sophistication which would render such analysis fruitful.

The SUNSHINE Project data contain correlated sets of alfalfa and soil samples from the Chicago milk shed, analyzed for strontium-90.

40/ Menzel, R.G. and Brown, I.C., Leaching of Fall-out and Plant Uptake of Fall-out. Bi-monthly Report, U.S. Dept. of Agriculture, March-April 1953.

The alfalfa samples ranged from 4.3 to 21 Sunshine Units. A Sunshine Unit (S.U.) is defined as one micro-microcurie (10^{-12} curie) of strontium-90 per gram of calcium. The top inch of the soil samples averaged 12 S.U., and the 1" - 6" depth of soil averaged 4.0 S.U. There was no correlation between the strontium-90 and calcium uptake and the plant concentration for strontium-90 was much higher than anticipated from the soil analyses. It was concluded that the strontium-90 content of alfalfa was largely due to direct fall-out on the plant rather than absorption of strontium-90 from the soil by the roots. The Lamont Laboratory analyzed corn leaves and obtained 0.5 S.U. from a 50% HCl leachate and less than 0.05 S.U. from the plant after leaching, demonstrating that most of the activity was on the surface of the plant and had not been taken up by root absorption from the soil.

These findings make it impossible to project current soil and bone deposition data because the non-recurring initial fall-out contamination is obscuring the biological uptake phenomena. The problem of the fraction of strontium-90 still unaccounted for also becomes more important because of these findings. If the strontium-90 still unaccounted for should be made available by descending to the earth's surface over a long period of time, there exists a mechanism for short circuiting the early parts of the biospheric chain and thereby increasing the final deposition of strontium-90 in bone over that expected from soil analyses. In other words, the root's preferential selectivity of calcium over strontium, as indicated previously, will not be operative for that fraction of the strontium-90 which falls out on the plants and is mechanically transported to the next step of the chain leading ultimately to the bones of humans.

From the point of view of human hazard, the major animal pathway of significance is that which deposits strontium-90 in milk and milk products. In certain areas of the world where, for example, small animals such as fish are eaten whole, this would be a modifying factor. In this report it will be considered that the cow and cow's milk con-

stitute the critical animal pathway leading to deposition of strontium-90 in human bone. This pathway may be expected to yield hazard levels to a significant population before alternate eating habits would be hazardous in other populations.

Experiments performed on cows indicate that the relative strontium-90 to calcium ratio in feed is reduced to 0.13 of its value by the time the strontium reaches the milk. The SUNSHINE Project data correlating the strontium-90 to calcium ratio in cows' milk with the ratio existing in their alfalfa feed indicate a reduction to approximately 0.15. This reduction is quite possibly brought about by the avidity of the bones of the cow for strontium-90. This avidity and hence the reduction of strontium-90 to calcium ratio in the milk might well disappear if the bones had been formed in an environment with the same strontium-90 to calcium ratio as was being fed at the time the milk was formed. For long-term hazard calculations, it is felt that this apparent factor of reduction in strontium-90 to calcium ratio should be ignored. Current interpretations of the data, therefore, should raise the values found in milk relative to that found in the animal feed when making hazard estimates for high concentrations of strontium-90. For the same reason a reduction in the strontium-90 to calcium ratio in fetal bones over that existing in the diet should not be used to support the possibility of a placental barrier in the human as a protective device for the part of the bones laid down *in utero*. Since the calcium laid down in fetal life constitutes about 2% of the total potential skeletal calcium, this phenomenon of placental barrier protection does not appear to be important quantitatively. The possibility of increased sensitivity to radiation in infant life, however, may magnify this beyond the proportion indicated by comparison with the final total of calcium in the adult skeleton.

The intake of strontium-90 by humans comes from four sources: air, water, plants, and animal products.

The amount of strontium-90 provided by inhalation of air

undoubtedly is a minute contribution to the total body burden in a highly contaminated environment where the other modes of transport are permitted to operate over a period of years. The possibility that inhalation during the actual fall-out time may provide particles that will lodge in the lung is not ruled out as a source of critical damage, but as yet there are no indications suggesting that it requires more than passing notice and an awareness that it should be watched for.

The water analyses of the SUNSHINE Project and other data indicate that water supplies such as reservoirs will not receive more than a normal share of fall-out based on surface area. The water-shed run-off water does not concentrate strontium-90 in the reservoir. It has also been shown that strontium-90 does not reach well water by leaching through the ground. It appears, therefore, that water will be a minor contributor to the total body burden in a highly contaminated environment.

There are no direct experimental data on humans with regard to metabolism and excretion on a quantitative basis. Inferences concerning amounts excreted and amounts deposited in bone are derived from animal data. In an attempt to attach significance to the amount of strontium-90 found in bone, reference is made to the total amount of fission products released, strontium-90 soil deposition and various levels in the soil-plant-animal-milk chain. The actual values obtained thus far are well below any hazard level. Their projection to hazard levels and their quantitative significance will become apparent when hazard calculations are discussed below.

It is important to remember that at the end of a year probably 5% or less of ingested strontium-90 is retained in bone. In terms of an equilibrium environment, this principle ceases to be important. Under these circumstances the ratio of strontium-90/calcium as it is taken in, corrected for any possible body discrimination between the two elements, becomes the important factor. The real situation may be a combination of a high initial intake followed by a continued lower

level of intake. Under these conditions the growing body would tend to stabilize at the lower level, but the added early high intake might be a factor worthy of assessment. For example, the suggestion has been made[41] that proper interpretation of 1 microcurie as the maximum permissible concentration in an adult, based on the radium type of experience, would allow between 1.5 and 3.0 microcuries strontium-90 in bone one year after initial exposure, in order to be equivalent to 0.5 to 1.0 microcurie 25 years later. The 1.5 to 3.0 microcuries would be 5% or less of the initially ingested dose. This reasoning points up the meaning of the body burden as found in the human radium cases with regard to extrapolating back to initial exposure. In a uniformly contaminated environment this problem will not require consideration.

In a uniformly contaminated environment it is possible to calculate the relationship between strontium-90 in the diet and that which will deposit in bone. Animal uptake studies of daily radio-strontium intake indicate that bone retention will, within a period of weeks, reach a maximum and that the relationship between the maximum bone radio-strontium level and the radio-strontium intake may be described by

$$A_s = \frac{A_f \times Sr_s}{Sr_f}$$

where

A_s = maximum attainable bone radio-strontium level

A_f = quantity of radio-strontium consumed per day

Sr_s = quantity of strontium in bone

Sr_f = quantity of strontium consumed per day

The bone strontium content has been measured and found to be approximately 0.67 gms. The daily intake of strontium is approximately

41/ Stover, C. N., Second Annual Conference on Plutonium and Mesothorium, University of Utah, June 1954.

1×10^{-3} gm.

Then to achieve a bone radio-strontium level of 1 microcurie, a continuous daily intake of 1.5×10^{-3} μc strontium-90 is necessary, since

$$A_f = \frac{1 \mu c \times 10^{-3} \text{ gm}}{.67 \text{ gm}}$$
$$= 1.5 \times 10^{-3} \ \mu c$$

Since, at present, the bone strontium content (Sr_s) and daily strontium intake (Sr_f) are relatively constant, the maximum attainable radio-strontium content (A_s) is determined by A_f. This means that the specific activity, i.e., the ratio of strontium-90 to stable strontium, in the diet is in the upper limit of the specific activity of bone strontium. Implicit is the corollary that for a fixed radio-strontium intake per day, an increase in stable strontium intake will result in a lower bone strontium specific activity if there are no alterations in the metabolism of strontium with an increase in daily strontium intake. Under these conditions of increased strontium intake the bone radio-strontium level will decrease, with time, to a new level, fixed by the specific activity of the food strontium.

Hazard Calculations. The evaluation of long-term hazard from radioactive fall-out has led to the identification of strontium-90 as the critical isotope on the basis of knowledge currently available. At present, Project GABRIEL and Project SUNSHINE are the two most serious studies concerned with strontium-90 evaluation. These studies accept strontium-90 as the most likely critical parameter for long-range hazard effects and have begun to accumulate and assess data concerning the actual strontium-90 situation as it exists in the world today. The RAND Corporation SUNSHINE Project report normalized its findings to a maximum permissible concentration (MPC) of 1.0 microcurie of strontium-90 lodged in the bone of a standard man. This enabled the physical data relating to fall-out to be interpreted in terms of a definitive amount of strontium-90 deposited in human bones. The actual signifi-

cance of this level in terms of hazard remains to be considered. As will be discussed below, the still more important problem of the significance of exceeding the MPC is quantitatively incapable of definition at present.

The RAND Project SUNSHINE Report created an idealized model for calculating the long-term hazard due to strontium-90. The essential sections needed for the problems considered in this report are quoted below:

"Neglecting the question of biologically effective dosages, the parameters necessary for assessing the hazard on a world-wide scale are:

"1. The fraction of strontium-90 available for distribution as a function of type of weapon, condition of burst, and meteorology.

> "We assume high-altitude bursts, with the immediate area of ground zero receiving no more than its proportional share of the fall-out debris....." (Uniform world-wide distribution of the available strontium-90.)

"2. Atmospheric or other natural storage mechanisms which might allow appreciable strontium-90 decay before it becomes available to humans.

> "Whether strontium-90 is stored in the atmosphere or in the biosphere, this consideration is not likely to increase our estimate ...." (of the number of airburst bombs to create a world-wide hazard).... "by more than a factor of two.

"3. Availability of strontium-90 in debris for transfer to the biosphere.

> "We believe the bulk of the strontium-90 to be plated out on the surface of the debris particles and also scavenged out in solution by rainfall." (On this assumption)...."it should be readily available for take-up by the biosphere. If our reasoning is incorrect and the strontium-90 is con-

tained inside insoluble particles, the calculation given below should then be regarded as highly pessimistic".... (i.e., that the estimate of fission yield to create a world-wide hazard may be too low.)

"4. Availability of natural strontium in soils.

"The parameter used here is 60 lb. of agriculturally available strontium per acre. We feel that over a period of time such as we are considering, more fixed strontium in the soil will become available. The better value lies somewhere between one and 20 times this amount. Having used the lower limit, our estimate in this respect is also pessimistic".... (i.e., too low.)

"5. Redistribution of strontium-90 by plowing, fertilizer, etc.

"Fall-out debris deposited on untilled soil is not leached down very effectively by rainfall. In agricultural areas .... however, the soil is constantly well mixed to an effective depth by the efforts of man. We also assume wash-off as relatively low. These considerations do in themselves...." (further tend to make the fission yield value calculated too low.)

"6. Content of natural strontium in bone.

"The average U.S. adult, normalized to the "Standard Man", contains 0.7 gm total strontium in his bones. This figure is probably .... accurate.

"On the basis of the above assumptions and other physical parameters, the preliminary SUNSHINE estimate of the nuclear bomb.... (fission) .... yield required to bring the population of the world up to Maximum Permissible Concentration is larger than 2.5×10^4 megatons (MT).

"The .... formula for arriving at the above figure is as follows:

"Let MT = the number of megatons of fission energy released,

W_{sr} = the number of grams of available natural strontium per square mile of area,

B = the number of grams of natural strontium fixed in the human skeleton at maturity;

T = the number of grams of strontium-90 fixed in the skeleton which is considered to be the level of interest (MPC or any other standard),

m = the number of grams of strontium-90 produced by the release of 1 MT of fission energy,

A = the area of the earth in square miles,

then

$$MT = \frac{1}{m}\frac{T}{B} \times W_{sr} \times A \text{ ....''}$$

Since there is little chance that m will be changed appreciably by future measurements and A is fixed, this relation can be simplified as follows (taking m = 1000 gm and A = 2×10^8 mi^2):

$$MT = 2 \times 10^5 \frac{T}{B} \times W_{sr} .$$

Taking T to be 5×10^{-9} gm (1 microcurie, the international MPC), B = 0.7 gm, and $W_{sr} = 1.7 \times 10^7$ gm, it is found that MT is 2.5×10^4, assuming uniform world-wide distribution.

It is instructive to apply the SUNSHINE model to the data collected thus far. The following table summarizes the situation.

TABLE 8

	Theoretical Lower Limit of the Threshold for Injury	Actual Values Measured To Date	Theoretical Calculation	Ratio Actual/Theoretical
Amount Fission Yield Detonated	2.5×10^4 MT	40 MT(1)	40 MT	1.0
Amount Sr^{90} Deposited	200µ gm/acre 0.129 gm/mi^2	.0084 5.38×10^{-6}(2)	.32 206×10^{-6}	.026
Amount Sr^{90} in Bone	1000 S.U.	0.5(3)	1.6	.31

(1) AFSWP data

(2) NYOO Fall-out Data

(3) Approximated from Lamont Laboratory SUNSHINE Data.

It can be seen that the 40 MT of fission yield released thus far has resulted in one-third of the expected body burden in human bone that would be predicted by the SUNSHINE model. Further examination of the table shows that only 2.6 per cent of the amount predicted by the model has actually fallen out in the United States as determined by cumulative soil analysis data. This indicates further that there is 12 times as much strontium-90 in human bone, based on the actual amounts available for uptake, as the SUNSHINE model would predict.

Mention should be made here that the strontium-90 soil figure of 1.08 mc/sq mi reported by the New York Operations Office of the Atomic Energy Commission is a theoretical figure based on the Hunter-Ballou table. Because of the known phenomenon of fractionation, a factor of 3 increase in the strontium-90 available for world-wide distribution from surface or tower bursts over the value that would be predicted on the basis of a gross fission product sample from the upper atmosphere appears reasonable and has been suggested by the New York Operations Office.[42/]

If the above calculations are corrected for fractionation of strontium, then instead of transport to bone being 12 times the expected value it is perhaps closer to 4 times this value. This is in agreement with experimental data suggesting that much of the early fall-out material is mechanically transported by plants rather than going through the soil-plant-animal biospheric chain.

This factor of a four-fold increase in deposition of strontium-90 in bone over the theoretically expected amount is not important if only a small total of the available strontium-90 is available for mechanical transport. But if the bulk of the strontium-90 which still

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42/ Eisenbud, M. and Harley, J.H., Radioactive Fall-out in the United States, Science 121:677, 1955 (May 13)

remains unaccounted for were to settle out slowly from the upper atmosphere over a period of many years and be subjected to this four-fold increase, then consideration must be given to this in future hazard calculations. This analysis is an oversimplification, since no account is taken of the decrease in world-wide distribution due to local fall-out, the relative efficiency of the fall-out collecting system and the possible increase, with time, in the number of Sunshine Units in bone due to the strontium-90 already fallen out.

The Lamont Laboratory data[43] suggest that the younger age groups in the more recent samples have a quantity of strontium-90 lodged in bone approximating 1.0 Sunshine Unit. In the United States 85% of body calcium comes from dairy products. If the young age group in an area of high dairy product intake is considered as the critical segment of the population for risk assessment, it would appear then that dairy products should be correlated with bone deposition. If the current data can be assumed to be a reflection of a maintained or increasing rate of uptake, then the bone of newborns should approach the strontium-90/calcium ratio present in milk products. Due to the lower saturation of the mother cow, there is a lowering of the potential ratio of strontium/calcium in the milk and calf. The same mechanism applies in the transport of strontium and calcium from cow's milk through the human mother to the fetus. Thus the current strontium-90 values in bone and milk products are lower than would be expected for the current fall-out, if the mother cow and the human mother had both grown up in this same contaminated environment.

Since the hazard calculation seeks to find the most sensitive population at risk we cannot accurately project current data to a situation of a long-term, maintained contaminated environment. The data can be extrapolated, to some extent, if allowance is made for the fact that eventually all parts of the chain transporting strontium-90 to

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43/ Kupl, J.L., Project SUNSHINE Annual Progress Report, March, 1955.

human bone will be in equilibrium with regard to strontium-90/calcium ratios peculiar to their particular position in the chain.

The continued availability of strontium-90 which has been created but has not yetfallen out, looms large as one of our most important present uncertainties in the world-wide deposition problem. Since new weapons tests continue to make available new strontium-90, the question of the rate of uptake of strontium-90 into the biosphere, year after year, of that deposited at any one time is difficult to resolve.

If the strontium-90 deposited is actively transported to bone only for a relatively short period of time, say one or two years, then the amount of strontium-90 which it is estimated may be deposited on soil without constituting a hazard can be raised considerably and, in fact, the strontium-89 would be an important contributor of radiation dose to bone on a gram-for-gram basis of produced material.

The very rapid uptake of strontium-90 by cattle due to direct ingestion of fall-out material is not significant with regard to the ultimate hazard calculation in terms of large scale fall-out over a limited period of time. The cattle bones under these circumstances would be taking up strontium-90 rapidly for a limited time only. This mechanism would probably spare the milk to some extent. After the first cycle, the regular biospheric chain should take over. The problem of continued uptake is thus more important than the short peak of uptake immediately following fall-out.

This discussion has omitted serious consideration of the problem of stratospheric storage and a continued slow fall-out over the years. If this mechanism is significant quantitatively, then a larger fraction of strontium-90 produced must be considered available for rapid uptake, than is available in the early fall-out period, even though this availability in time may be many years post-detonation.

It must be remembered that the current 1.0 Sunshine Unit now being found in the younger age group in this country should not necessarily rise with continued growth. Since this is a strontium-90/calcium

ratio, the current value will be maintained at 1.0 Sunshine Unit if the environment allows strontium-90 to be incorporated at the same rate which provided the current 1.0 Sunshine Unit. If the amount of strontium-90 available decreases with time, then as a child grows it will lay down relatively more calcium than strontium-90, and the Sunshine Unit value borne by the child will decrease. Thus the uncertainty relative to the continued availability for uptake of the strontium-90 created in past detonations but not yet deposited is still an unsettled problem.

Evaluation of the SUNSHINE Model Hazard Calculations. The Sunshine model listed six parameters necessary for assessing the strontium-90 hazard on a world-wide scale. Since the time this model was constructed, additional data have been collected so that it is worth while to re-examine these factors in the light of more recent knowledge.

The first assumption, that of uniform world-wide distribution of strontium-90, requires drastic correction. In summary, the situation is as follows:

1. 50-90% of gross fission product fall-out is accounted for locally for land surface bursts. For purposes of calculation, a figure of 60% appears reasonable. It will be recalled that the SUNSHINE model assumed a high air burst, which would involve a negligible local deposition of fall-out.

2. Less than 2% of the gross fission products created in detonations to date have been accounted for in world-wide fall-out.

3. One-third of the expected amount of strontium-90 on the basis of uniform distribution relative to other fission products was observed 80 miles downwind after the first CASTLE shot.

4. The world-wide gummed paper fall-out collections by the Atomic Energy Commission are, on the average, three times enriched in strontium-90 over the content in a normal gross sample of fission products.

5. A British calculation estimates 20 MT of gross fission

product activity still in the atmosphere.

The following table is presented to provide representative figures to use in calculations taking into account the factors listed above. Note that this table applies only to land surface bursts.

TABLE 9

	Gross Fall-out	Strontium-90
Local	60%	30%
Extended Local	10%	10%
World-wide deposited	1%	3%
World-wide not deposited	29%	57%
	100%	100%

Within the limits of accuracy of this type of analysis, it may be said that about half of the strontium-90 produced during a surface burst attack on an area the size of the United States will deposit within the country.

The SUNSHINE model, modified as noted above, can be applied to the calculation of the strontium-90 concentration possible in such a localized target area, assuming surface burst weapons:

$$\frac{3 \times 10^6 \text{ sq mi (area of U. S.)}}{2 \times 10^8 \text{ sq mi (area of earth)}} \times 100 = 1.5\%$$

Therefore: 1.5% of the area assumed available in the original model would receive 50% of the strontium-90 produced and

$$25{,}000 \text{ MT} \times .015 \times 2 = 750 \text{ MT}$$

is the amount needed to bring such an area to the 1 microcurie bone level, if the distribution over the area were assumed to be uniform. The uniform distribution assumption for local fall-out areas is NOT a valid one; in fact, roughly 10 times the yield figure stated, or 7500 MT, would have to be detonated on land surface in the United States to cover all of its area with at least the strontium-90 needed for 1 microcurie per man. It must be remembered that the SUNSHINE Model is

a theoretical construction and carries along all the inherent uncertainties, both physical and biological, which have been discussed in many of the preceding sections of this report. The numbers generated in the above paragraph are cited, not as absolutes, but as relative values, to point up a significant relationship: namely, that a local area may be large enough to be regarded as a critical geographical parameter. This local area will be above the safety levels for strontium-90 long before this situation exists on a world-wide basis if the contamination is brought about by surface bursts of nuclear weapons.

It may be superfluous to point out that the problems faced by those of the target population left alive after having been hit by 750 one megaton bombs would be likely to be such as to make that of accumulating one microcurie of strontium-90 in their bones over the next generation or so a very secondary consideration. It seems apparent that a military requirement which would result in mounting such an attack against a population would be so over-riding as to ignore the possibility of carcinogenesis in the remnants of the population some 20 years later.

On the other hand, if the 50% of the strontium-90 which does not fall out locally on the target area is distributed uniformly world-wide, then the bone deposition outside the local area would be 1.54×10^{-2} microcuries, and thus 2 x 25,000 MT = 50,000 MT of surface burst weapons on any target area would be required to bring the world outside that target area to the 1 microcurie bone level.

The second parameter in the SUNSHINE study, relating to atmospheric or other storage mechanisms, is still unresolved. There is considerable evidence pointing to stratospheric storage of radioactive material, but the quantity of material involved and the rate at which it descends are still in dispute. The British have estimated that half the material located above the tropopause will descend from the stratosphere into the troposphere every 5 years and that the material will

descend through the troposphere to the ground with a half time of 5 days. The basis for this estimate is unknown. It was transmitted by personal communication of R. Dudley of the Atomic Energy Commission, Division of Biology and Medicine. There is no known mechanism for bringing very finely divided particulate matter down through the temperature inversion which marks the tropopause, so that the reservoir of strontium-90 and other bomb debris now in the stratosphere may remain there much longer than the British estimate would indicate.

The third parameter cited in the SUNSHINE model concerns availability of strontium-90 in bomb debris for transfer to the biosphere. Most experimental work thus far indicates that the strontium-90 is readily available and moves more rapidly than expected through the biospheric chain. The data does not actually permit one to state the degree of availability of all the strontium-90 deposited but only that some unknown fraction is readily available. The possibility still exists that a certain proportion of the total strontium-90 created in a detonation may be trapped in insoluble particles and thus lost insofar as plant or animal uptake is concerned. There are some indications in the work at Hanford and U.C.L.A. on soil and crops that with passage of time strontium-90 is complexed with soil and rendered less available for biospheric uptake. No quantitative statements can be made as yet regarding this facet of the problem.

The fourth and fifth parameters are essentially concerned with the problem of concentration and uniform mixture of strontium-90 with its stable isotope. The determination of the amount of stable strontium in the soil is being worked on but firm values are not yet available. Uniform mixing of strontium-90 with stable strontium has been shown to be an invalid assumption for at least that part of the strontium-90 which has moved through the biosphere more rapidly than expected. Whether the remaining strontium-90 will mix and be traceable quantitatively is still unknown.

The last parameter concerns the strontium content of human

bone. The figure of 0.7 grams for the "Standard Man" is being borne out by more recent studies.

Thus the only really important correction to the SUNSHINE model which can be made at this time, then, relates to the first parameter of uniform distribution. Calculations indicative of how this can affect the results have been given above. It is important to recognize, however, that the SUNSHINE model deliberately strove to make the most "pessimistic" assumption possible; i.e., where a parameter value was in doubt, the value which led to the lowest possible estimate of fission yield was chosen. The range of uncertainty involved is such that had the upper limit been sought instead, it would have been greater than the lower limit of 25,000 MT by as much as a factor of a thousand.

Evaluation of the Strontium-90 MPC. As indicated previously, the 1.0 microcurie of strontium-90 maximum permissible concentration in man is based essentially on the following relationship:

$$\frac{Sr^{89}\ \text{Mouse}}{Ra\ \ \text{Mouse}} = \frac{(Sr^{89}\ \text{Human})}{Ra\ \ \text{Human}} = K\,\frac{(Sr^{90}\ \text{Human})}{Ra\ \ \text{Human}}$$

The non-bracketed values are observed and the others are calculated. The factor K is introduced to convert the strontium-89 experience to the strontium-90 equivalent.

The data leading to the establishment of 1.0 microcurie as the MPC for strontium-90 in man derive from the mouse experiments at the Argonne National Laboratory and the acceptance of 0.1 μgm of radium as being 0.1 of the lowest amount of that element in humans that has been found to be associated with tumor formation. The strontium-90 MPC value, therefore, is critically dependent upon the strontium-89 effects data originating from one laboratory and on the strontium-89/radium effects ratio derived from one species of lower animal and the extrapolation of this ratio to strontium-90 equivalent in man. This is obviously a rather tenuous basis for establishment of such an important standard. In addition, the radium experience in man is far from reliable. The clinical data are sparse; the collection of cases is not

sufficient to reliably associate damage with body burden except in the crudest fashion.

The inability to associate an increment of damage due to the mesothorium in the luminous dial workers indicates the degree of uncertainty in correlating damage found with particular body burdens of radium. It is fortunate that the data do strongly suggest a critical level of 0.5 - 1.0 microgram of radium body burden as the damage threshold.

Other factors regarding the risk involved in the anticipated strontium-90 contaminated fall-out area also must be considered. The radium experience underlying the establishment of the MPC consists of adults with a high intake over a relatively short period of time. The strontium-90 problem on the other hand is concerned first with young people having a continuous long-term intake. How to evaluate the MPC background data in terms of the different situations involved is still unresolved.

Effect of Higher Concentrations. The MPC concept has the relatively easy task of defining a safe level. Since the radium data tend to show a damage level of 0.5 - 1.0 microgram of radium and no damage in the cases below 0.5 microgram, these facts were of direct value in determining the MPC.

The analysis of the high levels of radium deposition do not show a proportional increase in amount of roentgenographic changes nor in their severity. Thus, current data do not permit a damage projection to higher levels than the MPC. In addition besides the rather arbitrary MPC which includes a safety factor, the lowest damage level actually observed can be defined. For radium this is considered to be 0.5 - 1.0 microgram, and, hence, for strontium-90 this becomes 5.0 - 10 microcuries.

The Project GABRIEL report for July 1954 states: "Using the radium to strontium-90 conversion factor of 10, one would estimate from these data that 1.0 microcurie strontium-90 adult body burden at

20 years after exposure would be safe, 5 microcuries would begin to produce radiographically demonstrable skeletal changes, and 50 - 200 microcuries might correspond to the LD_{50} in 20 years."

It is felt that even this statement cannot be depended upon because of the uncertainties discussed in prior sections relating to the state of knowledge of the deleterious effects of both radium and strontium-90 when lodged in the body. At present, it is perhaps fair to state that the MPC as derived may have to be lowered when applied to children and to longer periods of exposure than 20 years. No projection of current knowledge to levels of hazard beyond the MPC and, perhaps, the lowest estimated damage burden should be made.

The Iodine-131 Problem. Reports from Operation CASTLE that radioactive iodine was found in the urine of natives and test personnel have been substantiated by several test programs in this country.[44,45,46] In these programs, iodine-131 was detected in appreciable amounts in cattle and humans and found to have a biological half-life such as to indicate that it must have originated in the CASTLE series of nuclear detonations. The quantitative similarity in amount of iodine present in persons in the United States and in Honolulu as compared with the CASTLE test participants exposed to fall-out in the Pacific test area warrants consideration of this element both as a local fall-out hazard and as a world-wide contaminant.

As a consequence of nuclear fission and subsequent chain decay many isotopes of iodine are formed. Of these only two, iodine-131 and iodine-133, appear to have half-lives of a duration worth considering as potentially hazardous. Iodine-133 has a half-life of 22 hours as compared with that of 8 days for iodine-131, and thus at time of

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44/ Jones, H., Confirmation of Radioactivity in Thyroid of Various Animals, UCRL 2689.

45/ Van Middlesworth; Nucleonics, Vol. 12, Sept 1954.

46/ Hartgering, J.B., et al., unpublished, Army Medical Service Graduate School, 1955.

formation has approximately eight times the number of disintegrations per minute as iodine-131. They are produced by decay of tellurium-133 ($T_{1/2} = 63$ m.) and tellurium-131 ($T_{1/2} = 30$ hr), respectively, in the approximately equal amounts of one gram each per kiloton of fission yield.

Iodine is found to become quickly available for human deposition. Its metabolic pathway in the human will lead to approximately 20% of the amount received being deposited in the thyroid gland. The remaining 80% is excreted in a matter of several days. The action of this beta emitter upon thyroid tissue is in the nature of temporary to permanent cellular damage and is an effect which is sensitive to dose rate in addition to total dose, and hence to the high decay rate of iodine-131 and to the still higher rate of iodine-133 and other members of the iodine decay series.

The rapidity with which iodine appeared in the urine following a test detonation, coupled with the similar amounts present in animals of different eating habits, suggested that inhalation rather than ingestion was the probable route of entry. Further substantiation was later established when masked personnel showed urine free of iodine while unmasked personnel showed urinary radio-iodine prior to eating.[47] Thus, it appears that at least initially inhalation of iodine directly from the ambient air is the chief factor to consider.

As previously mentioned, the excretion of the non-thyroid deposited fraction takes several days. Thus, personnel briefly exposed to iodine-131 would be expected to have a corresponding excretion curve. That this is not the case has been demonstrated recently. Many curves reveal an 8-day half value time, which is the half-life of iodine-131. One conclusion appears to be that iodine-131, once having fallen out, remains for many days in the immediate environment. That it would remain hovering over an area for weeks in a stable atmosphere is deemed unlikely. Either of two alternatives is more acceptable:

47/ Trum, B.F., Lt. Col., V.C., Oak Ridge Institute of Nuclear Studies, Personal communication.

(a) that it deposits upon the ground adsorbed to a solid or liquid particulate and is subliming, continuing to contaminate the environmental air; or (b) that it deposits upon crops, is ingested by cattle and reaches the human through milk and milk products. Although this latter pathway has been demonstrated possible, it should not, on a basis of present information, be considered the only route after initial exposure has occurred.

Despite large individual variations in iodine uptake, data to date indicate: (a) that iodine-131 becomes available for wide distribution over the earth's surface from air, land surface and water surface bursts; and (b) fractionation appears to occur to the extent that urine samples indicate that iodine-131 tends to a global equilibrium state and, except for the factor of time of arrival, the doses to local and to distant personnel are comparable.

The maximum safely permissible amount of I-131 in the human body on a continuing exposure basis has been stated to be 0.3 microcuries.[48/] While this implies that for short periods of exposure a higher dose rate may be permissible, such as medical tracer doses of 5-50 microcuries, it should not be overlooked that the degree of thyroid tissue damage is a function of dose rate as well as dose and that consequently the tissue effect from acute and chronic doses of the same total amount are not comparable.

Thus, for purposes of setting meaningful fall-out exposure tolerances, this MPC for iodine-131 is misleading and inadequate. Although an exposure to fall-out is somewhat longer than the exposure from the ingestion of the medically used isotope, the similarity is sufficient to suggest employment of the "safe" single dose of 5-50 microcuries established by the medical profession. It is of interest to point out that no evidence of tissue damage has been reported for amounts under 100 microcuries.

If the MPC for iodine is exceeded, the significance would be of a lower order of magnitude than in the case of strontium-90 due to

48/ National Bureau of Standards Handbook 52.

the nature of the biological consequences involved.

Operation CASTLE Experience. Operation CASTLE has provided considerable information on the internal hazard due to fission product fall-out; however, the analyses reported thus far are subject to certain criticisms. If determinations of fission decay products present in the urine at a certain time post shot are extrapolated back to shot day in terms of body burden to bone and soft tissue, a much larger estimated than actual result will obtain unless the rate of uptake and initial rate of excretion are considered. Further, if a cumulative acquisition of internally deposited fall-out debris from a series of shots is extrapolated back to the date of the initial shot, a similarly larger calculated than actual dose will result.

In connection with the first criticism, the total body burden at one day after the shot for strontium-89 and iodine-131 is given as 1.6 microcuries and 6,400 microcuries, respectively. Even assuming strontium-89 to have been received as an acute single dose during actual fall-out, the more meaningful body burden would be the 82nd day value of 0.19 microcuries, representing as it does the actual bone burden.

Accepting for the sake of illustration the 1.6 microcurie value for the first day, a comparison of decay rates of strontium-89 versus strontium-90 indicates strontium-89 to have more than 100 times the activity of an equal amount of strontium-90 at day one. On this basis the total strontium-90 burden at day one would be 1.6×10^{-2} µc and on day 82, a value of 1.9×10^{-3} µc uncorrected for strontium-89 decay. This value of 1.9×10^{-3} microcuries represents roughly 1.9 SUNSHINE units, a value within the standard deviation of the world-wide value for SUNSHINE units of strontium in bone. In the case of iodine-131, the body burden at day one is given as 6.4×10^{3} microcuries, and if comparison of the decay rates of iodine-131 versus its shorter-lived isotope iodine-133 is made, the day one body burden of iodine-133 would be on the order of 6.4×10^{4} microcuries. These values of both iodine-131 and iodine-133 are well within normal therapeutic dose ranges for

thyroid suppression.

With regard to the second criticism, i.e., that if a cumulative acquisition of internally deposited fall-out debris from a series of shots is extrapolated back to the date of the initial shot, a larger than calculated dose will result; this may in part explain the extremely high iodine-131 value as extrapolated back 82 days to the first shot of the CASTLE series. Despite the fact that the subsequent shots were in one case only 130 KT and in the remaining four cases were water surface bursts, it is felt that the fraction of iodine-131, especially from the 13 MT YANKEE event 14 days before the urine study, considerably influenced the results. If as Figure 22 indicates, the body burden on the 82nd day is a cumulative function of all preceeding shots, then the calculated body burden for the first day is approximately 400 times too high. Thus

$$\frac{6.4 \times 10^4}{4.0 \times 10^2} = 1.6 \times 10^2$$

microcuries for the actual burden on the first day is considerably more within reason.

If it is assumed that iodine-131 is taken up biologically in comparable amounts regardless of proximity to the area of detonation, and that iodine and strontium alike accumulate in the body over a period of time from a series of shots rather than as a single acute dose, then support for these assumptions can be found in the CASTLE experience as well as in reasonable compatibility with subsequent experimental data.

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IV. CONCLUSIONS

The important conclusions which can be drawn from the study are summarized below:

A potential fall-out hazard is always associated with the detonation of a nuclear weapon, the amount of radioactivity being a function of the fission yield. This hazard may manifest itself on either a local or a world-wide basis or both, depending upon burst conditions.

The proportions of available activity falling out locally and world-wide are determined primarily by the location of the burst point relative to the surface of the earth, and secondarily by the character of the surface over which detonated, and by prevailing meteorological conditions.

Following a ground surface detonation, most of the gross radioactive materials are incorporated into earth particles, with the largest percentage, which falls out soon after the detonation, being on particles of 10 to 1000 microns diameter. The local fall-out after CASTLE Bravo shot is estimated to involve roughly 50% of the total activity available.

Contour scaling laws in current use in the megaton range are based on weapons which have a fission to fusion ratio Any deviation from this ratio will vary the amount of radioactivity deposited at any given distance from ground zero. As a first approximation it may be assumed that for a given total yield, the activity represented by a given contour is directly proportional to the fission yield. Raising the total yield of the weapon without raising the fission yield will spread the given amount of radioactivity over a larger local area.

Potentially lethal fall-out intensities resulting from land-surface bursts of nuclear weapons with fission yields in the megaton range are likely in each case to involve areas of thousands of square miles. Such lethal areas can be drastically reduced in size if the

population involved makes optimum use of available shelter. Quantitative statements regarding lethality carry the inherent uncertainties of the estimates relating percentage of deaths to levels of radiation.

The area involving a potential early hazard lies in a local pattern with its origin at ground zero, and arises primarily from the gamma radiation of the deposited fission products. The contribution by bomb formed tritium and other artificial radioactivity formed by neutron bombardment of soil and bomb debris does not appear to increase the hazard to any marked degree.

For a given burst condition, the size of the local hazard area is roughly proportional to the fission yield of the weapon.

Accurate pre-shot delineation of the local hazard areas likely to be involved following a nuclear detonation cannot be accomplished because of the sensitive wind-dependence of the deposition mechanism. Changes in the wind structure after shot time can radically alter the predicted deposition patterns based on wind soundings taken at or before shot time.

Approximate local hazard areas likely to be involved for a given nuclear weapon and burst condition can be determined in advance by currently available means. Approximate simplified elliptical contours can be drawn in a few minutes by untrained personnel and more exact contours can be calculated by hand or machine with somewhat greater effort and more complex inputs.

As much as 90% of the potentially lethal fall-out area from a land-surface burst nuclear weapon will lie outside the lethal area for blast and thermal effects, largely in a roughly elliptical pattern extending downwind from the burst point.

The radiation intensity in a gross fission product field decays in such a manner that shelter during the first few hours or days after fall-out begins is considerably more important than shelter at later times. Experience at field tests indicates that the $t^{-1.2}$ decay rate of mixed fission products holds sufficiently well to calculate

radiation rates in a fall-out field at times from five minutes to about one year after burst time.

The body is known to recover from at least a major portion of sublethal damage due to ionizing radiation. The rate of repair is unknown, but is believed to be of the order of 10% per day of the reparable damage remaining. Lethal dose estimates are well within the limits of the accuracy of the physical data upon which they are based.

In a fall-out area where the gamma radiation dose is sub-lethal, fission product beta and soft gamma emitters in the fall-out are a serious hazard only when in contact with the skin. A high degree of protection against this type of radiation is afforded by clothing which prevents fall-out material from contacting the skin.

There is a need for a high yield land-surface test detonation to fill in uncertainties in the present fund of knowledge on fall-out.

1 The primary long-term and world-wide hazards arise from the distribution by winds in the upper atmosphere of certain cancer-forming radioisotopes produced in the fission process, and their subsequent biological uptake by humans. Prominent among these are strontium-89, strontium-90 and iodine-131.

Approximately one gram each of strontium-89, strontium-90 and iodine-131 is formed per KT of fission yield. Because of fractionation, these elements are produced in such form and quantity as to favor their world-wide distribution as opposed to local deposition. However, for surface bursts the local contamination still remains the dominant factor.

2 The potential genetic effect of fall-out radiation on man is likely to be secondary in importance to short-term effects as well as to the hazard due to long-term cancer-producing effects. The chief uncertainties in this regard lie in the extrapolation of animal data to man. The manner of expression of the bulk of such radiation-induced mutations is, likewise, not certain. If manifested as miscarriages, this would greatly reduce the possible burden to society involved.

(3) Based on limited sampling in the upper atmosphere, it appears possible that the order of 20 MT fission product yield may currently be in the stratosphere and settling slowly to the earth. This value is one of the major uncertainties of our knowledge in the study of world-wide fall-out.

Available evidence indicates that strontium-90 is the critical radioisotope to consider in evaluating the cancer formation hazard of fall-out. From the point of view of world-wide distribution, a large degree of uncertainty exists because of the unknown amount of bomb debris remaining in the upper atmosphere and the possible rate at which this material will reach the biosphere. The phenomenon of fractionation is effective in influencing the amount of strontium-90 in the world-wide distribution system and thus further affects the amount available in the slow fall-out.

(4) The long-term strontium-90 hazard in the local fall-out area of land-surface nuclear weapons in all cases will exceed the world-wide hazard from the same detonation(s). There is no yield threshold for this local hazard. It exists in the local fall-out area of each land-surface burst nuclear weapon, regardless of yield, and affects those individuals who live off the produce of the contaminated area.

Strontium-90 deposits in human bones principally by way of uptake by the cow and passage to the milk. Hazard considerations depend upon several variables which cannot be quantitated at present.

(5) Radio-iodine has been shown to deposit in human thyroid tissue through inhalation and ingestion of fission products from distributions at locations far from the point of detonation. Due to the nature of the injury to the gland and to the relatively short half-lives of the radio-iodine series, the consequences of such depositions as far as can be determined from information to date will be secondary in importance to the radiostrontium hazard.

Current evaluation of the hazard due to internal deposition of various radioisotopes involves many uncertainties. At present, the

key value for assessment of any current or projected situation for any particular isotope is the so-called Maximum Permissible Concentration or MPC. For strontium-90 this is the maintained concentration which is believed to be one-tenth of the minimal amount necessary to cause cancer in an adult. Recent Project SUNSHINE analyses indicate that human bone specimens are approaching 0.001 of the MPC. Following the CASTLE series of shots, iodine-131 was identified in the urine of the Marshallese natives, Service personnel, in the area, and a small number of individuals in the United States, but was maintained for only a short period of time.

6 The long-term strontium-90 hazard from air burst nuclear weapons depends upon a world-wide distribution of the contaminant. It appears likely that the number of nuclear detonations, whether air or surface, required to cause a world-wide long-term strontium-90 hazard would be so large as to result in devastation of much of the habitable world area from the immediate destructive effects of the weapons. In such a case it is likely that any long-term effects on the population remaining would be of secondary importance.